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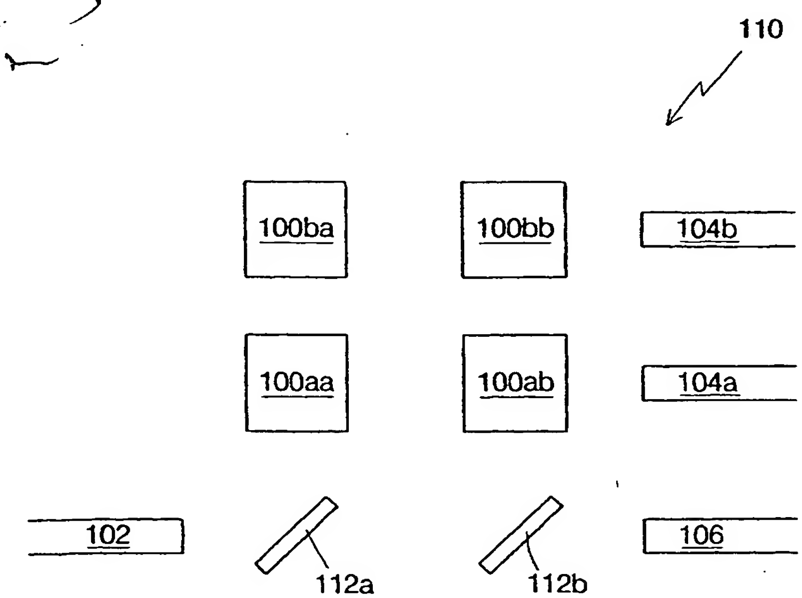

(57) Abstract: A device (110) for switching light of one of more discrete wavelengths to one or more output conduits (106). The device (110) includes fibers (a-b) for each wavelength and for each output conduit (106), an electroholographic switch (100aa-ab) for switching a controllable portion of the light of each wavelength to each output conduit (106), the electroholographic switches (100aa-bb) of a common output conduit (106) being optically coupled, the electroholographic switches (100aa-bb) of a common wavelength being optically coupled.

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ELECTROHOLOGRAPHIC WAVELENGTH SELECTIVE PHOTONIC SWITCH FOR WDM ROUTING

FIELD AND BACKGROUND OF THE INVENTION

The present invention relates to switch arrays useful in optical communications based on wavelength division multiplexing (WDM) and, more particularly, to a wavelength selective cross-connect and methods for its use.

An optical fiber communication channel is a light beam, propagating in a medium such as an optical fiber, whose intensity is modulated in time according to the data to be carried on the channel. In WDM, each of N channels is carried on the same optical fiber at a different carrier wavelength. In the current state of the art, such a WDM link can have up to 80 channels, at 80 discrete wavelengths separated by a wavelength difference $\Delta\lambda$ which may correspond to a frequency separation as small as 100 GHz.

Fast multidimensional switches are essential building blocks in high speed data communication systems, multimedia services, or high performance parallel computers. However, electronic implementations of such switches are close to their inherent limits. It is evident that it will not be possible to meet the demands of the emerging broadband communication applications by the existing electronic switching technology. Furthermore, electronic switching devices are not capable of direct integration with the optical fiber communication systems, which are becoming the dominant communications technology. Optical implementation of switching devices possesses several inherent advantages over their electronic counterparts.

Holographic optical elements and volume holograms have been used recently for two dimensional steering of light beams in optical interconnect networks, especially for highly parallel computer interconnects. However, such systems have generally relied, at least in the case of volume holograms, either on the use of a number of fixed holograms, the desired one of which is reconstructed using a reference beam selected by means of its wavelength or direction of incidence, or on the rewriting of the desired hologram in real time immediately before each steering action to be performed. Therefore, such holograms are not directly electrically

switchable, and thereby do not provide for simple system construction and high speed operation.

With the increase of the bit throughput rate in optical fiber communication systems by using WDM, cost effective light sources with very narrow spectral linewidths have been developed. The development of such lasers for optical communications has enabled the use of volume (thick) holograms as routing devices. Because such holograms are inherently extremely wavelength sensitive, their use had not previously been feasible commercially. The use of thick holograms now enables the routing of different WDM communication channels to different destinations in the same network, and thus allows three dimensional steering. However, to date, optical switches based on the use of prior art holograms, which are not directly electrically switchable, have not shown sufficient speed, nor do they possess sufficiently low cross-talk levels, to enable their use in the optical communication systems currently in use or under development.

Electroholography is a generic beam switching method based on controlling the diffraction from volume gratings by means of applying an electric field to the medium containing the grating. Electroholography can be implemented by the voltage controlled photorefractive effect realized in paraelectric photorefractive crystals wherein the electro-optic effect is quadratic. Here the grating is initially stored in the medium in the form of a photorefractive space charge, that induces an induced polarization grating and is consequently transformed by the quadratic electro-optic effect into an index of refraction (birefringence) grating when an electric field is applied to the medium. Alternatively, Electroholography can be implemented by the dielectric photorefractive effect where the grating is initially stored in the form of a grating of the dielectric constant, and is transformed by the quadratic electro-optic effect into an index of refraction (birefringence) grating when an electric field is applied to the medium. In the latter case the dielectric grating can be created by the creation of a spatial variation of the chemical composition in the crystal that induces a spatial variation of the phase transition temperature.

Aharon Agranat et al., in PCT/IL99/00368, which is incorporated by reference for all purposes as if fully set forth herein, teaches an electroholographic switch that is

particularly useful in optical communications. Electroholography enables the reconstruction process of volume holograms to be controlled by means of an externally applied electric field. Electroholography is based on the use of the voltage controlled photorefractive effect in the paraelectric phase, where the electro-optic effect is quadratic. Volume holograms stored as a spatial distribution of space charge in a paraelectric crystal can be reconstructed by the application of an electric field to the crystal. This field activates prestored holograms which determine the routing of data-carrying light beams.

The implementation of electroholography-based devices requires the use of a paraelectric photorefractive crystal with suitable properties, such as potassium tantalate niobate (KTN), strontium barium niobate (SBN), or especially potassium lithium tantalate niobate (KLTN), as taught by Hofmeister et al. in US Patents Nos. 5,614,129 and 5,785,898, which are incorporated by reference for all purposes as if fully set forth herein. KLTN doped with copper and vanadium is particularly suitable for use as the medium for electroholographic devices.

Unlike conventional holographic memory components based on conventional photorefractive crystals, which can be written and read only in the visible, electroholographic devices based on KLTN and similar materials can be operated in the near infra-red regions of the spectrum, including at 1.3 μm and 1.55 μm, wavelengths which are now commonly used in standard communication systems.

Figures 1A and 1B illustrate schematically the two states of an electroholographic 1x2 switch **100** of Agranat et al. that is based on a single paraelectric photorefractive crystal **10** that incorporates a prestored electroholographic (EH) grating. A pair of electrodes **12, 14** is deposited on two opposite faces of crystal **10**. Paraelectric photorefractive crystals **10** could be of a material such as KTN, SBN, or especially KLTN. When a voltage V, is applied across electrodes **12, 14,** a spatial modulation of the refractive index of crystal **10** is produced from the spatially modulated space charge field, set up according to the information carried by the volume hologram previously written into crystal **10**. Thus, a diffraction grating **17** is effectively established in crystal **10** by the application of the voltage difference **V** to electrode pair **12-14**.

Figure 1A shows one state of this switch **100** activated by applying a voltage V_0 (i.e. $V=V_0$) to crystal **10**. In this state, an optical signal inputted along a path **16** passes to an output port **18**. In this case, the residual power which remains in the input beam passes to an output port **20**. Figure 1B shows the second state of this switch **100**. Here a zero voltage (i.e. V=0) is applied to crystal **10**. Here the optical signal inputted along a path **16** passes to an output port **20**. In both states, optical signals carried on channels whose carrier wavelengths λ are not affected by grating **17** (as determined by the Bragg condition) pass unswitched to port **20**. A photodetector **21** may be placed in the optical path defined by port **20**, in which case the residual power remaining after input beam **16** traverses this switch **100** is used for management and monitoring purposes. as described in detail in IL 125241.

Figures 1C and 1D illustrate schematically the two states of an electroholographic 1x2 switch **100** of Agranat et al. that is based on two paraelectric photorefractive crystals **10** and **11**. Each crystal **10** or **11** incorporates a prestored electroholographic (EH) grating, with electrode pair **12, 14** deposited on two opposite faces of crystal **10** and electrode pair **13, 15** deposited on two opposite faces of crystal **11**. Paraelectric photorefractive crystals **10** and **11** could be of a material such as KTN, SBN, or especially KLTN. When a voltage V_0, is applied to either of the two pairs of electrodes **12**, **14** and **13, 15,** a spatial modulation of the refractive index of the respective crystal is produced from the spatially modulated space charge field. set up according to the information carried by the volume hologram previously written into crystal **10** or **11**. Thus, a diffraction grating (**17** in crystal **10**, or **19** in crystal **11**) is effectively established in crystal **10** or **11** by the application of the voltage to the electrode of the respective crystal.

Figure 1C shows one state of this switch **100** activated by applying a voltage V_0 (i.e. $V_1=V_0$) to crystal **10** and zero voltage (i.e. $V_2=0$) to crystal **11**. In this state, an optical signal inputted along a path **16** passes to an output port **18**. Figure 1D shows the second state of this switch **100**. Here a zero voltage (i.e. $V_1=0$) is applied to crystal **10** and voltage V_0 (i.e. $V_2= V_0$) is applied to crystal **11**. Here the optical signal inputted along a path **16** passes to an output port **20**. In both cases, the residual power which remains in the input beam is blocked by a block **21**. Block **21** may be replaced

by a photodetector, in which case the residual power remaining after input beam **16** traverses this switch **100** is used for management and monitoring purposes, as described in detail in IL 125241.

If V_1 and V_2 both are set equal to V_0, then part of the optical signal is diffracted to output port **18**, and the residual, that is not diffracted to output port **18**, is diffracted to output port **20**. If diffraction gratings **17** and **19** are set up with different grating spacings, to diffract light of different wavelengths, then switch **100** of Figures 1C and 1D functions as two switches **100** of Figures 1A and 1B configured in series.

The mechanism by which the electroholographic switch operates is based on the use of the voltage controlled photorefractive effect, as described by A. J. Agranat, V. Leyva and A. Yariv in "Voltage-controlled photorefractive effect in paraelectric $KTa_{1-x}Nb_xO_3CuV$", *Optics Letters*, vol. 14 pp. 1017-1019 (1989). The photorefractive effect enables the recording of optical information in a crystal, by spatially modulating its index of refraction in response to light energy it absorbs. The absorbed light photoionizes charge carriers from their traps to the conduction band (electrons) or the valence band (holes). The photoionized charge carriers are transported and eventually retrapped, forming a space charge field spatially correlated with the exciting illumination, and inducing a modulation in the index of refraction through the electrooptic effect. This mechanism is the basis for information storage in the form of phase holograms that can be selectively retrieved by applying the reconstructing (reading) light beam at the appropriate wavelength and angle.

Recently, it has been shown that it is also possible to introduce dipolar holographic gratings into photorefractive crystals by the introduction of a spatial modulation of the low frequency dielectric constant. This effect has been described by A. J. Agranat, M. Razvag and M. Balberg in "Dipolar holographic gratings induced by the photorefractive process in potassium lithium tantalate niobate at the paraelectric phase", *Journal of the Optical Society of America B*, vol. 14 pp. 2043-2048 (1997).

In the paraelectric phase, the efficiency of these effects can be controlled by applying an external electric field on the crystals during the reading (reconstructing) stage. Electroholography is based on this capability.

As indicated above, the physical basis of electroholography is the voltage controlled photorefractive (PR) effect. In general, the PR effect enables the recording of optical information in a crystal, by spatially modulating the index of refraction of the crystal in response to light energy that the crystal absorbs. In its simplest form the photorefractive effect is initiated by illuminating a crystal with the interference pattern of two mutually coherent beams. The absorbed light photoionizes charge carriers from their traps to the conduction band (electrons) or the valence band (holes). The photoionized charge carriers are transported and eventually retrapped, forming a space charge field that is spatially correlated with the exciting illumination, and inducing a modulation in the index of refraction of the crystal through the electrooptic effect.

In most PR crystals the electrooptic effect is linear. However, in PR crystals at the *paraelectric* phase the electrooptic effect is quadratic. Consequently, the induced changes in the index of refraction are given by:

$$\Delta n = \frac{1}{2} n_0^3 g_{eff} . P^2 \qquad (1)$$

where Δn is the induced change in the index of refraction, n_0 is the refractive index, g_{eff} is the effective quadratic electrooptic coefficient, and P is the low frequency electric polarization. When a space charge field $E_{sc}(\bar{r})$ is formed in the crystal, the polarization becomes:

$$P = \varepsilon[E_0 + E_{sc}(\bar{r})] \qquad (2)$$

where ε is the dielectric constant (which close to the phase transition obeys $\varepsilon/\varepsilon_0 >> 1$, where ε_0 is the permittivity of the vacuum, 8.854 x 10^{-12} F/m), E_0 is the externally applied field, and it is assumed that the polarization is in the linear region, where $P = \varepsilon_0(\varepsilon/\varepsilon_0 - 1)E$. Substituting equation (2) into equation (1) gives an expression for the spatial distribution of the space charge field, which includes 3 terms:

$$\Delta n(\bar{r}) = \frac{1}{2} n_0^3 g \varepsilon^2 \, [E_0^2 + 2E_0 E_{sc}(\bar{r}) + E_{sc}^2(\bar{r})] \qquad (3)$$

Consider the diffraction of a light beam with wavelength λ, which is incident on the crystal at an angle θ, and fulfills the Bragg condition given by

$$\Lambda = \lambda / 2 n_0 \sin\theta \qquad (4)$$

where Λ is the period of the grating formed by the PR process, and n_0 is the crystal

refractive index. The first term in equation (3) is spatially uniform and thus does not contribute to the diffraction. In principle, this term should affect the diffraction efficiency by detuning the Bragg condition, as it affects the bulk index of refraction n_0. However, in symmetric transmission gratings, the detuning of the Bragg condition is canceled out by the change in the internal angle of incidence caused by the refraction of the beam as it enters the crystal (Snell's law). The third term in equation (3) induces a grating with a period of $\Lambda/2$. Therefore, this grating is not Bragg matched with the incident beam and does not contribute to the diffraction. Thus, the only term in equation (3) that contributes to the diffraction is the second term. The amplitude of the index grating that it induces is given by

$$\delta\{\Delta n(\bar{r}) = n_{o3} g_{eff} \varepsilon^2 E_0 E_{sc}(\bar{r}) \qquad (5)$$

It can be seen that the space charge field spatial distribution is transformed into a modulation of the refractive index that diffracts light only in the presence of the externally applied electric field.

The diffraction efficiency of a plane wave diffracted by a sinusoidal phase transmission grating stored at the paraelectric phase is given by (H. Koglenik, "Coupled wave theory for thick hologram gratings", *Bell Syst. Tech. J.* vol. 48 pp. 2909-2949, 1969):

$$\eta = \exp(-\alpha d)\sin^2\left(\frac{\pi d}{\lambda \cos\vartheta} n_0^3 g\varepsilon\, E_0 E_{sc}\right) \qquad (6)$$

where d is the thickness of the crystal and it is assumed that the Bragg condition is satisfied. Note that this definition of the diffraction efficiency does not include scattering by defects of the crystal and reflection from the crystal facets. It can be seen from equation (6) that the applied external field E_0 controls the diffraction efficiency of the grating induced by the space charge.

Therefore, the use of the quadratic electrooptic effect enables an analog control of the reconstruction of the information. This is the voltage controlled PR effect discussed above.

As explained above, except for the case of symmetrical transmission holograms, due to the first term in equation (3), the application of an electric field on a crystal containing holograms in the form of distributed space charge, also causes a

detuning of the Bragg condition. This phenomenon has been described in detail by M. Balberg, M. Razvag, E. Refaelli and A. J. Agranat in "Electric field multiplexing of volume holograms in paraelectric crystals" *Applied Optics*, vol. 37, pp. 841 - 847 (1998).

KLTN is a photorefractive crystal designed to be operated in the paraelectric phase, where the photorefractive effect is voltage controlled. The composition and method of production of this crystal are described in US 5,614,129 and in US 5,785,898. The preferred chemical composition of the KLTN crystal used in switch **100** is $K_{0.9945}Li_{0.0055}Ta_{0.65}Nb_{0.35}O_3$. The phase transition temperature of the KLTN crystal used, as determined by measurement of the temperature dependence of the dielectric constant, is Tc=26°C. In order to improve the performance of the crystal, prior to writing the holograms, the crystals are subjected to a poling process in which they are gradually cooled at 0.5°C/minute from 40°C to 10°C under an external field of 2.1kV/cm, and then warmed-up to the operational temperature at the same rate. During operation, the crystal is held at 32°C, which is 6°C above its phase transition temperature, well within the paraelectric phase. The temperature is maintained by means of a stabilized thermoelectric element (not shown) in juxtaposition to crystals **10** and **11**.

SUMMARY OF THE INVENTION

According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, including: (a) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled.

According to the present invention there is provided a method for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, including the steps of: (a) providing, for each wavelength and for each output conduit, a respective electroholographic switch; (b) for each wavelength.

diverting the light of the each wavelength to the electroholographic switches of the each wavelength; and (c) for each electroholographic switch, setting a state of the each switch so as to further divert a desired portion of the light of the respective wavelength of the each switch to the respective output conduit of the each switch.

According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths to any of a first and second pluralities of output conduits, including: (a) a first module including: (i) for each wavelength and for each output conduit of the first plurality, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit of the first plurality, the electroholographic switches of a common output conduit of the first plurality being optically coupled, the electroholographic switches of a common wavelength being optically coupled; and (b) a second module including: (i) for each wavelength and for each output conduit of the second plurality, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit of the second plurality, the electroholographic switches of a common output conduit of the second plurality being optically coupled, the electroholographic switches of a common wavelength being optically coupled.

According to the present invention there is provided a device for switching light of any of a first and second pluralities of discrete wavelengths to any of a first and second pluralities of output conduits, including: (a) an uplink conduit; (b) a first module including: (i) for each wavelength of the first plurality of wavelengths and for each output conduit of the first plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii) for each wavelength of the first plurality, a mechanism for diverting, to the uplink conduit, the light of the each wavelength remaining after the controllable portion of the light of the each wavelength is switched to the first plurality of output conduits; and (c) a second module including: (i) for each wavelength of the second plurality of wavelengths and for each output conduit of the

second plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii) for each wavelength of the second plurality, a mechanism, optically coupled to the uplink conduit, for diverting the light of the each wavelength to the respective electroholographic switches while passing the light of all other wavelengths.

According to the present invention there is provided a device for switching light of any of a first and second pluralities of discrete wavelengths to any of a plurality of output conduits, including: (a) a first module including: (i) for each wavelength of the first plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the first plurality to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength of the first plurality being optically coupled; and (b) a second module including: (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the second plurality to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength of the second plurality being optically coupled.

According to the present invention there is provided a device for switching light of any of a plurality of discrete wavelengths from at least one of a plurality of input conduits to any one of a plurality of output conduits, including: (a) for each input conduit, a module including: (i) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength being optically coupled, and (ii) for each wavelength, a mechanism for diverting the light of the each wavelength from the each input conduit to the respective holographic switches while passing the light of all other

wavelengths; and (b) for each output conduit, a multiplexer for combining outputs of all the respective electroholographic switches into the each output conduit.

According to the present invention there is provided a device for converting light of any of a first plurality of discrete wavelengths to light of any of a second plurality of discrete wavelengths, the first and second pluralities being equal in number, and then switching the light of the second plurality of discrete wavelengths to any of a plurality of output conduits, including: (a) a first module including: (i) a plurality of transponders, equal in number to the first plurality of wavelengths, each transponder outputting light of a respective wavelength of the second plurality, and (ii) for each wavelength of the first plurality and for each transponder, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the first plurality to the each transponder, the electroholographic switches of a common transponder being optically coupled, the electroholographic switches of a common wavelength of the first plurality being optically coupled; and (b) a second module including: (i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the second plurality to the each output conduit, the electroholographic switches of a common output conduit being optically coupled, the electroholographic switches of a common wavelength of the second plurality being optically coupled.

According to the present invention there is provided, in an optical communication system wherein signals are carried in a plurality of channels, each channel including light of a respective discrete wavelength, an add-drop multiplexer, for replacing at least one input signal with a corresponding at least one output signal on a respective subplurality of the channels, including: (a) an uplink conduit; (b) a drop module including: (i) a plurality of diversion conduits, (ii) for each wavelength of the subplurality and for each diversion conduit, an electroholographic switch for switching a controllable portion of the light of the each wavelength of the subplurality to the each diversion conduit, the electroholographic switches of a common diversion conduit being optically coupled, the electroholographic switches of a common wavelength of the subplurality being optically coupled, and (iii) a mechanism for

diverting the light of the each wavelength of the subplurality to the respective electroholographic switches while passing the light of all other wavelengths to the uplink conduit; and (c) an add module including: (i) a plurality of substitution conduits, and (ii) a mechanism for diverting light of the wavelengths of the subplurality from each substitution conduit to the uplink conduit.

According to the present invention there is provided, in an optical communications system wherein signals are carried in a plurality of channels via a common conduit, each channel having a respective discrete wavelength, a device for tapping the channels, including: (a) for each channel, a respective electroholographic switch for diverting a controllable portion of the signals of the each channel from the common conduit.

According to the present invention there is provided an electroholographic switch, for switching light of a certain wavelength, including: (a) a crystal of a photorefractive material including a plurality of electroholographic gratings, the electroholographic gratings being spaced apart laterally within the crystal; and (b) for each electroholographic grating, two electrodes for activating the each grating.

According to the present invention there is provided an optical switch including a paraelectric photorefractive material, wherein is stored a plurality of superposed holograms whose reconstruction is controllable by means of an applied electric field.

According to the present invention there is provided a method for determining a level of amplification of an optical signal for switching the optical signal to a primary output conduit, the method including the steps of: (a) providing at least one electroholographic switch for switching the optical signal to the primary output conduit; (b) diverting a first portion of the optical signal through the electroholographic switch to the primary output conduit and a second portion of the optical signal through the electroholographic switch to a secondary output conduit; (c) detecting a power of the second portion; and (d) based on the detected power of the second portion, adjusting a power of the first portion.

According to the present invention there is provided a method for analyzing at least one quality characteristic of an optical signal, the method including the steps of:

(a) providing an electroholographic switch for diverting at least a portion of the optical signal for analysis; (b) diverting the at least a portion of the optical signal for analysis; and (c) analyzing the at least a portion of the optical signal to determine the at least one quality characteristic.

According to the present invention there is provided a method of communication wherein optical signals are transmitted through an optical communication network, the optical signals being encoded in a plurality of channels propagating in an optical medium, the method including the steps of: (a) diverting only a portion of the optical signals in each channel while a remainder of the optical signals in each channel continues to propagate in the optical medium; (b) converting each portion to an electronic signal; and (c) managing the network in accordance with the electronic signal.

The basic device of the present invention receives, from an input conduit, a plurality of concurrent WDM data streams (channels) *i*, each carrying data at a different carrier wavelength λ_i, diverts one or more of the data streams to any desired degree, from no diversion to almost full diversion, to one or more output conduits, and passes the undiverted remainder of the data streams to a common output conduit. Most typically, the input and output conduits are optical fibers.

Figure 2 shows, schematically, a basic embodiment of the basic device of the present invention. Device **110** receives a plurality of concurrent WDM data streams from an input optical fiber **102**. The two data streams whose carrier wavelengths are λ_1 and λ_2 are partially or totally diverted to output optical fibers **104a** and **104b**. The remainder of the input data streams continues undiverted into common output optical fiber **106**.

Device **110** includes two wavelength-specific filters **112a** and **112b** and four switches of the type illustrated in Figure 1, switch **100aa**, switch **100ab**, switch **100ba** and switch **100bb**, arranged in a matrix as shown. Filter **112a** diverts the data stream whose carrier wavelength is λ_1 to switches **100aa** and **100ba**. Filter **112b** diverts the data stream whose carrier wavelength is λ_2 to switches **100ab** and **100bb**. Filters **112** are demultiplexing narrow-band filters, for example, interference filters or Bragg grating filters. Such filters are well-known in the art, and are used, for example, in the

DWDM1F series of demultiplexers available from E-TEK dynamics, Inc. Of San Jose CF, USA. Alternatively, filters **112** are photorefractive crystals, such as crystals **10** and **11**, with diffraction gratings such as gratings **17** and **19** incorporated therein and activated by appropriate voltages to provide nearly full diversion of their respective data streams.

Switches **100** are illustrated as being positioned in a square grid. In general, the grid is oblique, with the grid angles and the grating spacings of the holographic gratings of switches **100** chosen, in accordance with the Bragg condition, so that switches **100aa** and **100ba** act only on light in a narrow band of wavelengths (narrower than $\Delta\lambda$) around carrier wavelength λ_1 and pass light of all other wavelengths, and so that switches **100ab** and **100bb** act only on light in a narrow band of wavelengths around carrier wavelength λ_2 and pass light of all other wavelengths. In the preferred embodiment of device **110**, the grid is in fact square (or, more generally, rectangular; the grid angle is 90^o), in order to obtain as compact a device **110** as possible and to simplify the production of device **110** with regard to issues such as alignment and collimation. The grating spacings of the holographic gratings are chosen to obtain Bragg angles of 45^o relative to the corresponding wavelengths.

By appropriately adjusting the voltages applied to switches **100aa** and **100ba**, the data stream of carrier wavelength λ_1 is diverted to any desired degree, from no diversion to almost total diversion, to either or both of output optical fibers **104**. Similarly, by appropriately adjusting the voltages applied to switches **100ab** and **100bb**, the data stream of carrier wavelength λ_2 is diverted to any desired degree, from no diversion to almost total diversion, to either or both of optical fibers **104**. The diversion of the data stream of carrier wavelength λ_1 is totally independent of the diversion of the data stream of carrier wavelength λ_2. Either output optical fiber **104** may receive only the data stream of carrier wavelength λ_1, only the data stream of carrier wavelength λ_2, both data streams or neither data stream. Switches **100ab** and **100bb** have no effect on the data stream of wavelength λ_1, so that the data stream of wavelength λ_1 passes unaffected through switches **100ab** and **100bb**. Thus, each row of switches **100** in device **110** functions as an optical coupler.

In the most preferred embodiment of device **110**, all four switches **100** are

fabricated in the same photorefractive crystal. Such an array or matrix of electroholographic switches constitutes an invention in its own right.

In one enhanced embodiment of device **110**, the columns of switches **100** end in detectors that receive light of wavelengths λ_1 and λ_2 not diverted by switches **100**. These detectors convert the undiverted light to electrical voltages that are proportional to the intensities of the undiverted light. These detectors typically are integrated in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis.

In a second enhanced embodiment of device **110**, the columns of switches **100** end in additional electroholographic switches for diverting the light of wavelengths λ_1 and λ_2 not diverted by switches **100** to a common uplink conduit.

Third and fourth enhanced embodiments of device **110** includes mechanisms for verifying that switches **100** actually switch the data streams as intended. In the third enhanced embodiment, a diversion mechanism such as a beamsplitter or yet another electroholographic switch intervenes between each row of switches **100** and the corresponding output optical fiber **104**. The diversion mechanism diverts a preferably controllable portion of the light emerging from that row of switches **100** to a detector. In the fourth enhanced embodiment of device **110**, each column of switches **100** is provided with a light source that emits coherent light at a wavelength other than the wavelength switched by that column of switches **100**. This light also is diverted, at least partially, by the holographic gratings of switches **100** of that column, but in a direction other than the row direction, to be detected by appropriate detectors.

Compound devices of the present invention are based on basic devices of the present invention used as modules.

In a first compound device of the present invention, based on two modules, the second module lacks filters **112**, and the light not switched by the columns of switches **100** of the first module goes directly to the columns of switches **100** of the second module, to be switched, entirely or in part, to output optical fibers **104** of the second module.

In a second compound device of the present invention, also based on two modules, the first module is the enhanced module, described above, in which the

columns of switches **100** end in additional electroholographic switches that divert the light emerging from the columns to a common uplink conduit. The uplink conduit then serves as input conduit **102** of the second module.

In a third compound device of the present invention, also based on two modules, both modules are the enhanced module, described above, in which the columns of switches **100** end in additional electroholographic switches that divert the light emerging from the columns to a common uplink conduit, and the uplink conduit is shared by both modules. In addition, the rows of switches **100** of the two modules are coupled into common output optical fibers **104**, either by optically coupling the rows of switches **100** of the first module to the rows of switches **100** of the second module, or by joining output optical fibers **104** of the first module to output optical fibers **104** of the second module at y-junctions.

In a fourth compound device of the present invention, based on several modules, each with its own input optical fiber **102**, corresponding output optical fibers **104** of the various modules lead to common multiplexers. The inputs of each multiplexer then are combined into a common output fiber leading from that multiplexer.

In a fifth compound device of the present invention, based on two modules, the first module has an equal number of rows and columns of switches **100**, and the output conduits of the first module are not optical fibers **104**, but instead are transponders, each of which converts input light into similar light at a respective output wavelength. Each transponder is optically coupled to a respective column of switches **100** of the second module.

An add-drop multiplexer of the present invention, for removing data streams at carrier wavelengths λ_1 and λ_2, from a collection of concurrent data streams that include data streams at these and other wavelengths, and substituting for them other data streams at carrier wavelengths λ_1 and λ_2, includes a drop module and an add module. The drop module is a basic device of the present invention. Output optical fibers **104** of the drop module are diversion conduits that carry the data streams being dropped to their respective destinations. The add module receives the surviving data streams from the drop module, and also receives input from substitution conduits that

carry substitution data streams at their respective carrier wavelengths, λ_1 or λ_2. The substitution data streams are merged with the input from the drop module using optical components such as y-junctions, or alternatively using electroholographic switches in a manner similar to that used in the second enhanced embodiment of device **110** to merge undiverted light of wavelengths λ_1 and λ_2 to a common uplink conduit.

A holographic tap of the present invention diverts portions of selected channels from a common optical fiber, using electroholographic switches **100** specific to the carrier wavelengths of the selected channels. The diverted light is converted to electronic signals by suitable detectors, and the signals are used for network management functions. For example, in a holographic tap downstream from an amplifier, the voltages applied to switches **100** are adjusted to equalize the powers in the tapped channels.

The wavelength specific photonic switching technology provides a way to "access" the optical transmissions without intervening the all-optical path, i.e. the data path. It is achieved by using the residual ("left-over") signal from the switching of the optical signals in ELECTROHOLOGRAPHIC switches. The residual signal is a well-defined portion of the original signal, so it can used to restore the characteristics of the original wave for network management analysis. The residual wavelength can be diverted to an output conduit as optical signal and/or converted to electrical signals by detector for power, error, and data analysis. Thus, these signals can be analyzed by network management devices which are able to determine the efficacy of transmission according to the analysis of the residual wavelength.

As described in greater detail below, a number of different embodiments of optical switches are suitable for use with these network management devices, although of course other implementations of optical switches could also be used. The network management devices of the present invention can be used to ensure the quality of the optical signal transmission and to detect when such quality of transmission falls below a minimum level at any one optical switch.

It will be appreciated that the various features of the enhanced and compound embodiments of the device of the present invention may be used together in a single

enhanced/compound device of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

FIG. 1 illustrates, schematically, the operation of the prior art electroholographic switches upon which the present invention is based;

FIG. 2 is a schematic illustration of the most basic embodiment of a basic device of the present invention;

FIG. 3 is a schematic illustration of an enhanced embodiment of the device of FIG. 2;

FIG. 4 is a schematic illustration of another enhanced embodiment of the device of FIG. 2;

FIG. 5 is a schematic illustration of a third enhanced embodiment of the device of FIG. 2;

FIG. 6 is a schematic illustration of a compound device of the present invention;

FIG. 7 is schematic illustration of another compound device of the present invention;

FIG. 8 is a schematic illustration of a third compound device of the present invention;

FIG. 9 is a schematic illustration of a fourth compound device of the present invention;

FIG. 10 is a schematic illustration of a fifth compound device of the present invention;

FIG. 11 is a schematic illustration of a sixth compound device of the present invention;

FIG. 12 is a schematic illustration of the use of an electroholographic tap of the present invention for power equalization;

FIG. 13 is a schematic illustration of an add-drop multiplexer of the present invention;

FIG. 14 is a schematic illustration of an alternative add module for the add-drop multiplexer of FIG. 13;

FIG. 15 illustrates an alternate method of power equalization in the add-drop multiplexer of FIG. 13;

FIGs. 16A and 16B are side and front views of two electroholographic switches fabricated on the same photorefractive crystal;

FIG. 17 is a schematic block diagram of a preferred detection module according to the present invention;

FIG. 18 is a schematic block diagram of a preferred optical signal power level determiner according to the present invention;

FIG. 19 is a first preferred embodiment of the management analyzer according to the present invention, dedicated to a single channel;

FIG. 20 is a second preferred embodiment of the management analyzer according to the present invention, capable of switching channels; and

FIG. 21 is a third preferred embodiment of the management analyzer according to the present invention, in a mixed configuration.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The present invention is of a wavelength specific cross-connect which can be used to switch input optical data streams among a plurality of output channels. Specifically, the present invention can be used for cross-connecting channels, for grouping, for broadcasting and for multicasting.

The principles and operation of a wavelength specific cross-connect according to the present invention may be better understood with reference to the drawings and the accompanying description.

The basic devices of the present invention are depicted herein with only two rows and two columns of switches **100** only for illustrational simplicity. Typically, a basic device of the present invention includes 32 columns and 8 rows of switches **100**.

Referring again to the drawings, Figure 3 is a schematic illustration of an enhanced embodiment **120** of the basic device of the present invention. Device **120** includes, in addition to the components of device **110**, two detectors **114**, such as

photodiodes, at the output ends of respective columns of switches **100**, two beamsplitters **116** at the output ends of respective rows of switches **100**, and detectors **118**, similar to detectors **114**, for receiving light diverted by beamsplitters **116** from reaching the respective output optical fibers **104**.

Detector **114a** detects the intensity of light diverted to switches **100aa** and **100ba** by filter **112a** but not diverted by switches **100aa** and **100ba** to output optical fibers **104**. Similarly, detector **114b** detects the intensity of light diverted to switches **100ab** and **100bb** by filter **112b** but not diverted by switches **100ab** and **100bb** to output optical fibers **104**. Detectors **114** convert the light incident thereon to electrical voltages that are proportional to the intensities of that light. These detectors typically are integrated in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis. Thus, these detectors enable the implementation of *noninterfering* network management. Unlike the prior art method of network management, in which optical channels are converted to electronic signals, network management functions are implemented by manipulating these electronic signals, and , finally, these electronic signals are converted back to optical signals, the network management method of the present invention is based on electronic manipulation of signals created from diverted *portions* of the optical channels, while the undiverted portions of the optical channels continue to propagate in the optical fibers of the network.

One such application of detectors **114** and the associated electronics is to power equalizing. The fraction of the light diverted by any of switches **100** is a known function of the voltage applied to the switch. Therefore, the powers of the channels switched into output optical fibers **104** can be computed from the intensity readings obtained by detectors **114**. The voltages applied to switches **100** then can be adjusted in a feedback loop to equalize the powers of the channels of carrier wavelengths λ_1 and λ_2 in output optical fibers **104**.

Beamsplitter **116a** diverts to detector **118a** a fraction of the light that emerges from switches **100aa** and **100ab**. Similarly, beamsplitter **116b** diverts to detector **118b** a fraction of the light that emerges from switches **100ba** and **100bb**. The intensities measured by detectors **118** are used to verify that switches **100** are in fact

diverting the desired proportions of light received from filters **112** to output optical fibers **104**, as functions of the voltages applied to switches **100**. The electrical signals produced by detectors **114** and **118** also may be used in selftest mode, to verify that the voltages applied to switches **100** do indeed activate the desired (row,column) pairs.

Alternatively, wide-band electroholographic switches are used in place of beamsplitters **116**. A wide-band electroholographic switch is an electroholographic switch similar to switch **100** but having a holographic grating that interacts with and diffracts a wider range of wavelengths, at each incidence angle, than the wavelength difference $\Delta\lambda$ that separates the distinct carrier wavelengths. Wide-band electroholographic switches have the advantage over beamsplitters **116** of being tunable: the fraction of the light diverted to detectors **118** is adjustable by adjusting the voltages applied to the switches.

Figure 4 is a schematic illustration of an enhanced embodiment **130** of the basic device of the present invention. Device **130** includes, in addition to the components of device **110**, two sources **122** of coherent light beams **126** and four detectors **124**. Sources **122** may include, for example, suitable lasers and suitable collimation optics. Source **122a** directs a collimated beam **126a** of coherent light, at a wavelength outside the band $\lambda_1 \pm \Delta\lambda/2$, down the left-hand column of switches **100**. Beam **126a** is diffracted by the holographic gratings of switches **100aa** and **100ba**, and is thereby at least partially diverted by switches **100aa** and **100ba** to respective detectors **124aa** and **124ba**. Because the wavelength of beam **126a** differs from λ_1, diffracted beams **128aa** and **128ba** emerge from switches **100aa** and **100ba** at a different angle, according to the Bragg condition, relative to incident beam **126a**, than the angle at which switches **100aa** and **100ba** divert light received from filter **112a** towards output optical fibers **104**. To illustrate this difference, Figure 4 is drawn with the angle at which switches **100aa** and **100ba** divert light received from filter **112a** being a right angle, and the angle between incident beam **126a** and diffracted beams **128aa** and **128ba** being an oblique angle. Similarly, source **122b** directs a collimated beam **126b** of coherent light, at a wavelength outside the band $\lambda_2 \pm \Delta\lambda/2$, down the right-hand column of switches **100**. Beam **126b** is diffracted by the holographic

gratings of switches **100ab** and **100bb**, and is thereby at least partially diverted by switches **100ab** and **100bb** to respective detectors **124ab** and **124bb**. Because the wavelength of beam **126b** differs from λ_2, diffracted beams **128ab** and **128bb** emerge from switches **100ab** and **100bb** at a different angle, relative to incident beam **126b**, than the angle at which switches **100ab** and **100bb** divert light received from filter **112b** towards output optical fibers **104**. Furthermore, beams **126a** and **126b**, by virtue of having wavelengths different from λ_1 and λ_2, respectively, pass through filters **112** without being diverted towards common output optical fiber **106**. Therefore, none of the light from sources **122** enters output optical fibers **104** and **106** to contaminate the data streams propagating therein. As in the case of detectors **118** of Figure 3, the intensities measured by detectors **124** are used to verify that switches **100** are in fact diverting the desired proportions of light received from filters **112** to output optical fibers **104**, as functions of the voltages applied to switches **100**.

Figure 5 is a schematic illustration of an enhanced embodiment **140** of the basic device of the present invention. Device **140** includes, in addition to the components of device **110**, two more electroholographic switches **100'** at the output ends of respective columns of switches **100**, and an uplink optical fiber **136** that receives light from switches **100'**. Switch **100'a** is specific to light of wavelength λ_1, and directs light of wavelength λ_1, emerging from switches **100aa** and **100ba**, towards uplink optical fiber **136**. Similarly, switch **100'b** is specific to light of wavelength λ_2, and directs light of wavelength λ_2, emerging from switches **100ab** and **100bb**, towards uplink optical fiber **136**. Common output optical fiber **106** wraps around to become an input optical fiber **134** for switches **100'**. Thus, the light entering device **140** from input optical fiber **102** at wavelengths other than λ_1 and λ_2 is merged with the light of wavelengths λ_1 and λ_2 that is not diverted to output optical fibers **104**, and uplink **136** serves as the actual common output optical fiber of device **140**.

In an embodiment of the basic device of the present invention that includes the features of both embodiment **120** of Figure 3 and embodiment **140** of Figure 5, the voltages applied to switches **100'** direct only a portion of the light that emerges from their respective columns of switches **100** to uplink optical fiber **136**. The rest of this light is detected by detectors such as detectors **114**.

Figure 6 is a schematic illustration of a compound device **150** of the present invention, based on two modules, a module **110'** that is almost identical to device **110**, and a module **120'** that is similar to device **120**, but lacks filters **112**, beamsplitters **116** and detectors **118**. Module **110'** includes two switches, **100aa** and **100ba**, for switching light of wavelength λ_1, and two switches, **100ab** and **100bb**, for switching light of wavelength λ_2. Module **120'** includes two switches, **100ca** and **100da**, for switching light of wavelength λ_1, and two switches, **100cb** and **100db**, for switching light of wavelength λ_2. As in device **110**, switches **100aa** and **100ab** divert a portion of their respective inputs to output optical fiber **104a**, and switches **100ba** and **100bb** divert a portion of their respective inputs to output optical fiber **104b**. Similarly, switches **100ca** and **100cb** divert a portion of their respective inputs to an output optical fiber **104c**, and switches **100da** and **100db** divert a portion of their respective inputs to an output optical fiber **104d**. Switches **100aa** and **100ba** are coupled optically to switches **100ca** and **100da** by an intermediate optical fiber **142a**. Similarly, switches **100ab** and **100bb** are coupled optically to switches **100cb** and **100db** by an intermediate optical fiber **142b**. Optionally, switches **100** of module **110'** are coupled to switches **100** of module **120'** across free space, without the intervention of intermediate optical fibers **142**. Thus, device **150** functions as a basic device of the present invention with double the number of output optical fibers **104**.

Figure 7 is a schematic illustration of a compound device **160** of the present invention based on two devices **140** used as modules. Uplink optical fiber **136** of the left hand module **140** leads into input optical fiber **102** of the right hand module **140** to provide input to the right hand module **140**. As in device **140** of Figure 5, filters **112** of the left hand module **140** divert light of wavelengths λ_1 and λ_2, respectively. Filters **112** of the right hand module **140** divert light of two other wavelengths, λ_3 and λ_4, respectively. Thus, device **160** functions as a basic device of the present invention that switches twice as many data streams to twice as many output optical fibers **104**.

Figure 8 is a schematic illustration of a compound device **170** of the present invention based on two modules, **140'** and **140''**, that are almost identical to device **140**. Module **140'** includes a wavelength-specific filter **112a** that diverts light of wavelength λ_1 to two switches, **100aa** and **100ba**, and wavelength-specific filter **112b**

that diverts light of wavelength λ_2 to two switches, **100ab** and **100bb**. Switches **100aa** and **100ab** divert part or all of the light they receive to an intermediate optical fiber **164a**. Switches **100ba** and **100bb** divert part or all of the light they receive to an intermediate optical fiber **164b**. Light not diverted by filters **112a** and **112b** is conducted by an intermediate optical fiber **162** to module **140''**, where a wavelength-specific filter **112c** diverts light of wavelength λ_3 to two switches, **100ac** and **100bc**, and a wavelength-specific filter **112d** diverts light of wavelength λ_4 to two switches, **100ad** and **100bd**. Switches **100ac** and **100ad** divert part or all of the light they receive to output optical fiber **104a**. Switches **100bc** and **100bd** divert part or all of the light they receive to output optical fiber **104b**. Light not diverted by filters **112c** and **112d** enters common output optical fiber **106**. Intermediate optical fiber **164a** couples filters **100aa** and **100ab** optically to filters **100ac** and **100ad**, and the light diverted by filters **100aa** and **100ab** to filters **100ac** and **100ad** via intermediate optical fiber **164a** passes through filters **100ac** and **100ad** to output optical fiber **104a**. Similarly, intermediate optical fiber **164b** couples filters **100ba** and **100bb** optically to filters **100bc** and **100bd**, and the light diverted by filters **100ba** and **100bb** to filters **100bc** and **100bd** via intermediate optical fiber **164b** passes through filters **100bc** and **100bd** to output optical fiber **104b**. As in device **140**, common output optical fiber **106** wraps around to become input optical fiber **134**, and light received by module **140'** from input optical fiber **134** joins light not diverted by filters **100aa**, **100ba**, **100ab** and **100bb** to be directed by electroholographic switches **100'a** and **100'b** to an intermediate optical fiber **166**. In module **140''**, light received from intermediate optical fiber **166** joins light not diverted by filters **100ac**, **100bc**, **100ad** and **100bd** to be directed by electroholographic switches **100'c** and **100'd** to uplink optical fiber **136**. Thus, device **170** functions as a basic device of the present invention that switches twice as many data streams to the same number of output optical fibers.

Figure 9 illustrates, schematically, an alternative way to couple modules **140'** and **140''** to produce a compound device **180** of the present invention. Intermediate optical fibers **164**, instead of being optically coupled to filters **100** of module **140''**, are coupled directly to output optical fibers **104** at y-junctions **172a** and **172b** In addition, uplink optical fibers **136** of modules **140'** and **140''** are mutually coupled at

y-junction **172c**. Thus, device **180** emulates a basic device of the present invention that switches twice as many data streams to the same number of output optical fibers.

Figure 10 is a schematic illustration of a compound device **190** of the present invention based on three devices **110** used as modules. All three output optical fibers **104a** lead to a multiplexer **182a**, which receives the data streams that are switched in devices **110** to output optical fibers **104a** and combines these data streams into a combined data stream on a common output optical fiber **184a**. Similarly, all three output optical fibers **104b** lead to a multiplexer **182b**, which receives the data streams that are switched in devices **110** to output optical fibers **104b** and combines these data streams into a combined data stream on a common output optical fiber **184b**. Device **190** serves as a 3 x 2 x 2 optical cross-connect, that cross-connects two wavelengths from three inputs to two outputs.

Figure 11 is a schematic illustration of a compound device **220** of the present invention based on two modules **110''** and **110'''**. Module **110''** is almost identical to device **110**. In module **110''**, wavelength-specific filter **112a** diverts light of wavelength λ_1 to two switches **100aa** and **100ba**, and wavelength-specific filter **112b** diverts light of wavelength λ_2 to two switches **100ab** and **100bb**. Switches **100aa** and **100ab** divert all or part of the light they receive to a transponder **222a**. In general, a transponder is a receiver-transmitter device that automatically transmits a signal when the proper interrogating signal is received. In this case, transponder **222a** reshapes, regenerates and optionally retimes the signals it receives and outputs those signals using a carrier wave of a wavelength λ_3 different from either λ_1 or λ_2. Similarly, switches **100ba** and **100bb** divert all or part of the light they receive to a transponder **222b** that reshapes, regenerates and optionally retimes the signals it receives and outputs those signals using a carrier wave of a wavelength λ_4 different from either λ_1 or λ_2 or λ_3. Module **110'''** is similar to device **110**, but lacks wavelength-specific filters **112**. Instead, light emerging from transponder **222a** traverses a column of switches **100ac**, **100ad** and **100ae** that are specific to light of wavelength λ_3, and light emerging from transponder **222b** traverses a column of switches **100bc**, **100bd** and **100be** that are specific to light of wavelength λ_4. Switches **100ac** and **100bc** divert all or part of the light they receive to output optical fiber **104c**; switches **100ad** and

100bd divert all or part of the light they receive to output optical fiber **104d**; and switches **100ae** and **100be** divert all or part of the light they receive to output optical fiber **104e**. Note that the order of the rows and columns of switches **100** in module **110'''**, as drawn in Figure 11, is transposed relative to the order of the rows and columns of switches **100** in module **110''**. As in basic embodiment **140**, common output optical fiber **106** of module **110''** serves as an input optical fiber **134** of module **110'''** for the purpose of uplink.

As in basic embodiment **120** of Figure 3, the columns of module **110''** and the rows of module **110'''** terminate in detectors **114** and **115** that typically are integrated in electronic devices that perform system functions such as error detection, network monitoring and analysis, and data monitoring and analysis.

The purpose of device **220** is wavelength conversion. In this application, module **110''** must be operated only in cross-connect mode, and not in broadcast or multicast mode: only one switch **100** per column and only one switch **100** per row may be activated. The wavelength conversion is determined by which switches **100** are activated. If switches **100aa** and **100bb** are activated, then part or all of the data stream of carrier wavelength λ_1 is converted to a data stream of carrier wavelength λ_3, and part or all of the data stream of carrier wavelength λ_2 is converted to a data stream of carrier wavelength λ_4. Similarly, if switches **100ab** and **100ba** are activated, then part or all of the data stream of carrier wavelength λ_1 is converted to a data stream of carrier wavelength λ_4, and part or all of the data stream of carrier wavelength λ_2 is converted to a data stream of carrier wavelength λ_3. Module **110'''** effects cross-connect, broadcast and multicast of the data streams of carrier wavelengths λ_3 and λ_4.

Figure 12 is a schematic illustration of an electroholographic tap **200** of the present invention, used to equalize the powers of channels of carrier wavelengths λ_1, λ_2 and λ_3, propagating to the right in a common optical conduit such as an optical fiber **206**, after these channels have been amplified by an amplifier **202** such as an erbium-doped fiber amplifier. Such equalization is needed because amplifier **202** typically has a response that is not flat as a function of wavelength. Therefore, even if the three channels have the same power upon entry to amplifier **202**, these channels

may have different powers upon emerging from amplifier **202**. Electroholographic tap **200** includes three electroholographic switches **100**, each specific to one of the three wavelengths λ_1, λ_2 and λ_3, and three detectors **210** that are similar to detectors **114**. A portion of the light of wavelength λ_1 entering tap **200** is diverted by switch **100a** to detector **210a**, a portion of the light of wavelength λ_2 entering tap **200** is diverted by switch **100b** to detector **210b**, and a portion of the light of wavelength λ_3 entering tap **200** is diverted by switch **100c** to detector **210c**. The remainder of the light entering tap **200** from the left exits tap **200** to the right and continues to propagate in optical fiber **206**.

Also shown in Figure 12 is a control module **212**, for power equalization, that receives electronic signals from detectors **210** and applies control voltages to switches **100**. The combination of detectors **210** and control module **212** provides a feedback loop for equalizing the power of the channels of carrier wavelengths λ_1, λ_2 and λ_3. Control module **212** receives electrical signals from detectors **210** that are representative of the intensities of the light diverted to detectors **210** by switches **100**. Control module **212** then adjusts the voltages applied to switches **100** to equalize the powers of the channels of carrier wavelengths λ_1, λ_2 and λ_3 in optical fiber **206**.

Figure 13 is a schematic illustration of an add-drop multiplexer **230** of the present invention. Add-drop multiplexer **230** is based on two modules, a drop module **231** that is identical to device **140**, and an add module **234**. The purpose of add-drop multiplexer is to remove, from the plurality of concurrent WDM data streams coming in on input optical fiber **102**, the data streams having carrier wavelengths λ_1 and λ_2, and to substitute for these two data streams two other data streams having carrier wavelengths λ_1 and λ_2. Output optical fibers **104a** and **104b** serve as diversion conduits: the input data streams having carrier wavelengths λ_1 and λ_2 are diverted to either or both of output optical fibers **104a** and **104b** by drop module **231**.

The remaining data streams proceed via uplink optical fiber **136** to add module **234**. Also input to add module **234** are two substitution data streams, one having carrier wavelength λ_1 and the other having carrier wavelength λ_2. The substitution data stream having carrier wavelength λ_1 is introduced to add module **234** via an input optical fiber **236a** functioning as a substitution conduit. The substitution data stream

having carrier wavelength λ_2 is introduced to add module **234** via an input optical fiber **236b** functioning as a substitution conduit.

Add module **234** includes two optical components **232a** and **232b** that merge the data streams having carrier wavelengths λ_1 and λ_2, and that enter add module **234** via input optical fibers **236**, with the data streams that enter add module **234** via uplink optical fiber **236**. The two substitution data streams are merged with the other data streams by optical components **232**, and all the data streams input to add module **234** emerge via an extension **240**, of uplink optical fiber **136**, that functions as the output conduit of add-drop multiplexer **230**.

Three implementations of optical components **232** are possible. In the first implementation, optical components **232** are y-junctions, similar to y-junctions **172** of device **180** of Figure 9. In the second implementation, optical components **232** are wide-band electroholographic switches. In the third implementation, optical components **232** are narrow-band electro-optical switches such as electroholographic switches **100**.

Under the second and third implementations of optical components **232**, uplink optical fiber **136** is coupled optically to components **232** in the same way that input optical fiber **136** of Figure 5 is coupled optically to electroholographic switches **100'**; input optical fiber **236a** is coupled optically to component **232a** in the same way that switches **100aa** and **100ba** are coupled optically to electroholographic switch **100'a** of Figure 5; and input optical fiber **236b** is coupled optically to component **232b** in the same way that switches **100ab** and **100bb** are coupled optically to electroholographic switch **100'b** of Figure 5. Under the second implementation of optical components **232**, each of input optical fibers may carry several data streams of several carrier wavelengths (*e.g.*, λ_{1a}, λ_{1b}, etc. on input optical fiber **236a** and λ_{2a}, λ_{2b}, etc. on input optical fiber **236b**), depending on the bandwidths of wide-band electro-optical switches **232**, as long as the two sets of carrier wavelengths are disjoint.

Preferably, under the second and third implementations of optical components **232**, drop module **231** includes the features of both device **140** and device **120**. Wide or narrow band electro-optic switches **232** divert only a portion of the light from their

respective input optical fibers **236** to extension **240**. The light not diverted by switches **232** is detected by detectors **238** that are similar to detectors **114** and **118**, and the electrical signals from detectors **114**, **118** and **238** are used by a control system to adjust the voltages applied to electroholographic switches **100** of drop module **231** and to electro-optic switches **232**, in order to equalize the power of the substitution data streams with the power of the data streams they replace.

It will be appreciated that add module **234** may serve as multiplexer **182** of device **190** of Figure 10.

Figure 14 is a schematic illustration of an alternative add module **234'** of the present invention. Add module **234'** combines features of basic embodiments **120** and **140** of Figures 3 and 5 to provide, in one device, the separate advantages of the second and third implementations of add module **234**. Both input optical fiber **236a** and input optical fiber **236b** carry substitution data streams of both carrier wavelengths λ_1 and λ_2. Controllable portions of these data streams are directed to electroholographic switches **100'a** and **100'b** by electroholographic switches **100aa**, **100ab**, **100ba** and **100bb**. The remainder of the substitution data streams continue to propagate rightward to be discarded, or to be detected for network management purposes by detectors (not shown) that are similar to detectors **114**. Switches **100'a** and **100'b** merge a controllable portion of the data streams incident thereon from below with the data streams entering from the left via uplink optical fiber **236**, and the merged data streams exit rightward via extension **240**. The portions of the data streams incident on switches **100'a** and **100'b** from below, that are not merged with the data streams entering via uplink optical fiber **136** from the right, are detected by detectors **238'a** and **238'b**, respectively that are similar to detectors **238**; and the resulting electronic signals are used for network management functions such as power equalization.

Figure 15 illustrates an alternate method of implementing power equalization in add-drop multiplexer **230**. An output optical fiber **104** of drop module **231** and a corresponding input optical fiber **236** of add module **234** are provided with respective electroholographic taps **200'** and **200''** that share a common control module **212** that receives electronic signals from the detectors of taps **200'** and **200''** and that controls

the voltages applied to the electroholographic switches of taps **200'** and **200''**. From the signals received from the detectors of tap **200'**, control module **212** infers the power levels of the data streams in output optical fiber **104**. Control module then adjusts the voltages applied to the electroholographic switches of tap **200''**, with feedback from the detectors of tap **200''**, to make the power levels of the substitution data streams in input optical fiber **236** equal to the power levels of the corresponding data streams in output optical fiber **104**.

The scope of the present invention also includes electroholographic switches in which the paraelectric photorefractive crystals **10** or **11** include several superposed holographic gratings **17** or **19**, each grating **17** or **19** having a different spacing, for switching light of several different wavelengths according to the Bragg condition. Figure 1 serves to illustrate these kinds of switches, with the understanding that reference numerals **17** and **19** indicate, not single holographic gratings, but several superposed holographic gratings. Note that all the superposed gratings are activated together by the same voltage difference across the same electrode pair **12, 14** or **13, 15**. Such switches provide an alternative to switches **100** of device **130**. Specifically, each alternative electroholographic switch is fabricated with two holographic gratings **17** or **19** per crystal **10** or **11**, each grating having a different spacing. One of the gratings is used to implement the switching function of the electroholographic switches, *i.e.*, the switching of light of wavelength λ_1 or λ_2. The other grating is used to divert a beam **126**, to an extent proportional to the extent to which the data stream of carrier wavelength λ_1 or λ_2 is diverted to an output optical fiber **104**. This alternative allows more flexibility in the positioning of detectors **124** relative to their respective electroholographic switches.

Figures 16A and 16B are schematic side and front views, respectively, of electroholographic switches **100aa** and **100ba** fabricated in and on a single photorefractive crystal **250**. Switch **100aa** includes a holographic grating **17aa**, within crystal **250**, sandwiched between two electrodes **12aa** and **14aa** on opposite surfaces **252** and **254** of crystal **250**, and a holographic grating **19aa**, within crystal **250**, sandwiched between two electrodes **15aa** and **13aa** on opposite surfaces **252** and **254** of crystal **250**. Similarly, switch **100ba** includes a holographic grating **17ba**,

within crystal **250**, sandwiched between two electrodes **12ba** and **14ba** on opposite surfaces **252** and **254** of crystal **250**, and a holographic grating **19ba**, within crystal **250**, sandwiched between two electrodes **15ba** and **13ba** on opposite surfaces **252** and **254** of crystal **250**. It has been found that the electric field established across grating **17aa, 19aa, 17ba** or **19ba** by the voltage difference applied to its respective electrode pairs **12aa-14aa, 13aa-15aa, 12ba-14ba** and **13ba-15ba**, is confined to the vicinity of that grating **17aa, 19aa, 17ba** or **19ba**, and does not cause cross-talk with the other gratings. Preferably, to ensure that there is no cross-talk among the gratings, the polarities of successive electrode pairs are alternated, as shown: the successive electrodes on surface **252** are grounded electrode **15aa**, active electrode **12aa**, grounded electrode **15ba** and active electrode **12ba**; and the successive electrodes on surface **254** are active electrode **13aa**, grounded electrode **14aa**, active electrode **13ba** and grounded electrode **14ba**. The term "active electrode" is used herein to refer to the electrode to which voltage **V**, relative to ground, is applied, as illustrated in Figure 1.

For illustrational simplicity, Figure 16 shows only a single column of switches **100** of device **110** fabricated in a single crystal **250**. It will be appreciated that all four switches **100** of device **110** could be fabricated in a single photorefractive crystal, as a two dimensional array of switches **100**. It also will be appreciated that in an embodiment of device **110** in which filters **112** are implemented as electroholographic switches, filters **112** also could be fabricated in the same photorefractive crystal as switches **100**.

In an alternative embodiment of switches **100aa** and **100ba**, electrodes **12** and **14** are deposited on the same side of crystal **250** and, electrodes **13** and **15** are deposited on the same side (not necessarily the side on which electrodes **12** and **14** are deposited) of crystal **250**.

In addition to the various embodiments of the devices of the present invention for a wavelength specific photonic switch, several management devices are contemplated as being within the scope of the present invention. These management devices enable the residual portion of the original, or undiverted, signal to be analyzed, for network management purposes such as error detection for the optical

signal. Preferred embodiments of these management devices are illustrated in Figures 17-21, including a preferred detection module and exemplary output according to the present invention (Figure 17); a preferred optical signal power level determiner according to the present invention (Figure 18); and three preferred embodiments of the management analyzer according to the present invention (Figures 19-21). It is to be understood that although reference is made specifically to the wavelength specific photonic switching devices described in Figures 1-14 above, the management devices of Figures 17-21 could also optionally be used with other types of optical switching devices. Each of these management devices is able to determine a quality characteristic of the optical signal, as described in greater detail below.

Figure 17 is a schematic block diagram of an illustrative detection module according to the present invention. A detection module **300** according to the present invention is in communication with an electro-optical switch according to the present invention, such as any of the electro-optical switches of Figures 1-14 for example. A switch interface **302** receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface **302** then passes the residual signal to a photo-detector **304**. Optionally and preferably, switch interface **302** is connected to a plurality of photo-detectors **304**, each photo-detector **304** corresponding to a specific wavelength if the electro-optical switch is a wavelength specific switch.

Each photo-detector **304** converts the received light from the residual signal into a voltage. The voltage is then passed to each of a plurality of voltage comparators, including a high voltage comparator **306** and a low voltage comparator **308** as shown. High voltage comparator **306** and low voltage comparator **308** are collectively an example of an analyzer according to the present invention. High voltage comparator **306** compares the received voltage to a maximum preset high threshold. If the received voltage is greater than this high voltage threshold, then a high voltage indication is generated by high voltage comparator **306**. The high voltage indication indicates that the level of the input signal of the switching core is saturated, such that this saturation is a quality characteristic of the optical signal.

For example, high voltage comparator **306** could cause an LED to become lit.

As another example, high voltage comparator **306** could send such a high voltage indication to a host interface **309**. Host interface **309** preferably features a first electronic hardware input **310** for receiving the high voltage signal from high voltage comparator **306**. This high voltage signal is the digital result of the comparison for determining the high power indication. Host interface **309** also preferably features an output alarm module **312** for notification of a system manager or other component of the network when the high voltage indication has been received. Output alarm module **312** is optionally implemented as software, hardware or firmware, or a combination thereof.

Similarly, low voltage comparator **308** compares the received voltage to a minimum preset low threshold. If the received voltage is less than this low voltage threshold, then a low voltage indication is generated by low voltage comparator **308**. The low voltage indication indicates that the level of the input signal to the optical switching core is below the minimum value, such that this low level is a quality characteristic of the optical signal. As for high voltage comparator **306** above, such low voltage comparator **308** could cause an LED to become lit, or alternatively low voltage comparator **308** could send such a low voltage indication to host interface **309**. Host interface **309** preferably features a second electronic hardware input **314** for receiving the low voltage signal from high voltage comparator **306**. Host interface **309** also preferably features an output alarm module **312** for notification of a system manager or other component of the network when the high voltage indication has been received.

Preferably, host interface **309** is able to configure the high and low voltage detection thresholds for high voltage comparator **306** and low voltage comparator **308**, respectively. The threshold is defined by setting the level of the reference voltage to the comparator. This reference voltage can be provided by a variable resistor or D/A. More preferably, host interface **309** is able to receive configuration instructions from an outside source, such as a system manager (not shown), for determining how to configure these thresholds. For example, the system manager could optionally request host interface **309** to decrease the threshold of high voltage comparator **306** and/or to increase the threshold for low voltage comparator **308**, for more precise control of the

optical signal. Of course, the threshold for only one of high voltage comparator **306** and/or low voltage comparator **308** could also optionally be adjusted.

Figure 18 is a schematic block diagram of an optical signal power level determiner according to the present invention. A signal power level determiner **316** again is in communication with an electro-optical switch according to the present invention, such as any of the electro-optical switches of Figures 1-14 for example. Signal power level determiner **316** is in communication with switch interface **302**, which may be the same or different than the switch interface of Figure 17. Switch interface **302** again receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface **302** then passes the residual signal to a transistor **318**. Transistor **318** translates the received residual light signal to voltage. The voltage is then converted into a digital signal by an A/D (analog to digital) converter **320**, with the resolution determined according to the requirements of the system. Transistor **318** and A/D converter **320** are collectively another example of an analyzer according to the present invention.

The digital value of the power the received light signal is latched into a per channel register **322**, such that this power is a quality characteristic of the optical signal. The value from register **322** is then transferred to host interface **309**, and then to the host (not shown) upon request by the host. The host request includes the command itself from the host, which specifies the number of the selected channel or selected wavelength. The information is selected (not shown), and is transferred to the host.

Optionally and preferably, signal power level determiner **316** also features a configurable threshold indicator (not shown) as for detection module **300** of Figure 17. The configurable threshold indicator would compare the received digital values to a predefined high threshold and to a predefined low threshold, and would then more preferably generate both the same alarm indication and/or status register as necessary. Most preferably, the threshold indicator is fully configurable, as such configurability is essential for fine adjustments of the power monitoring and detection of small deviations from the expected power levels for the optical signal.

Optionally, both A/D (analog to digital) converter **320** and the threshold converter are implemented as a DSP or as an analog ASIC chip. Optionally, the output of the detector can be used as input for error detection using a dedicated device for SONET/SDH data overhead monitor.

Optionally, the output of the detector is used to determine the data rate and protocol using a dedicated device for clock and data recovery.

Figures 19-21 show three different preferred embodiments of exemplary management analyzers according to the present invention. Each such management analyzer is able to analyze the optical signal in order to assess signal quality and to perform error detection, in order to determine a quality characteristic of the optical signal. Although the following description centers upon the analysis of the optical signal for the physical layer (layer 1) of the networking model, it is understood that such analysis could also be used for higher level protocols and data structures, such as for IP packets (layer 3) transmitted over the network.

Figure 19 shows a first embodiment of an exemplary management analyzer **324** according to the present invention. In this embodiment, management analyzer **324** is dedicated to a particular wavelength of optical signal. Management analyzer **324** again is in communication with an electro-optical switch, or tap, according to the present invention, such as any of the electro-optical switches of Figures 1-14 for example. Such communication is effected through switch interface **302**, which again may be the same or different than the switch interface of Figures 17 or 18. Switch interface **302** again receives a residual signal from the electro-optical switch (not shown), which has split off this portion of the optical signal for analysis. Switch interface **302** then passes the residual signal to a receiver **326**, which converts the optical signal to an electronic digital signal, preferably as well as performing the clock recovery with a clock **328**. In this embodiment, receiver **326** is dedicated to a single wavelength of light. The serial (single bit) electronic signals are translated into a parallel format of 8, 16 or 32 bit signals by a data translator **330**. Receiver **326**, clock **328** and data translator **330** are collectively yet another example of an analyzer according to the present invention.

The translated data is then passed to an analysis engine **332**. Analysis engine

332 performs any necessary statistical analyses on the translated data in order to assess the optical signal. For example, analysis engine **332** could determine the available bandwidth by assessing the relative frequency of high threshold power overload, as such an overload indicates saturation of the electro-optical switch and hence of the network. In addition, analysis engine **332** could calculate the relative variation in the optical signal, which is an assessment of the control of signal transduction through the optical network and which is another quality characteristic of the optical signal.

According to a preferred embodiment of analysis engine **332**, the information which is collected about the optical signal is relatively simple, such as information provided by traffic counters for example. Such information is more preferably supplied to the host through host interface **309**, and is then retrieved at a predefined sampling rate. Preferably, the recovered clock is used for identification of the data rate. Optionally and preferably, analysis engine **332** is constructed as a combination of DSP, CPU and ASIC chips and/or firmware, in order to provide data analysis with a sustained rate of at least 2.5 Gbps. Optionally and more preferably, analysis engine **332** is shared by a plurality of receivers **326** for receiving light of a plurality of different wavelengths for the optical signal.

Figure 20 shows a second embodiment of an exemplary management analyzer according to the present invention. In this embodiment an exemplary management analyzer **334** is again connected to switch interface **302**, as for the embodiment shown in Figure 19. However, management analyzer **334** now features a single receiver **336**, connected to an optical channel selector **338**. Optical channel selector **338** selects an optical channel and directs light of that wavelength to receiver **336**. Preferably, optical channel selector **338** selects light from each channel in turn, in a "round robin" selection. Optionally and more preferably, optical channel selector **338** is configurable, for example through instructions from the host (not shown) through host interface **309**. The remaining components of management analyzer **334**, including clock **328**, data translator **330** and analysis engine **332**, are implemented as for Figure 19. Optionally and preferably, the optical channel selector is an ELECTROHOLOGRAPHIC switch.

Figure 21 shows a third exemplary embodiment of a management analyzer

according to the present invention, with a mixed configuration which permits both single channel selection for optical signal analysis and continuous optical signal monitoring. Optionally, the analyzer incorporates functionality for power level monitoring. Optionally and more preferably, functionality for error detection is also featured. A management analyzer **340** is again connected to switch interface **302**, as for the embodiment shown in Figures 19 and 20. As for Figure 20, management analyzer **340** again features single receiver **336** connected to optical channel selector **338**. Optical channel selector **338** again selects an optical channel and directs light of that wavelength to receiver **336**. Other components of management analyzer **340**, including host interface **309**, clock **328**, data translator **330** and analysis engine **332**, are implemented as for Figures 19 and 20.

In order to provide the continuous optical signal monitoring, management analyzer **340** features a photodetector **342**, which converts the received optical signal into a digital voltage signal for further analysis. Preferably, analysis engine **332** is able to detect any alterations in the power level out of an acceptable range, whether above or below that range. Optionally and more preferably, such detection is used to identify the data rate and detect data errors, which are further examples of quality characteristics of the optical signal. More preferably, such detection is coupled to threshold analysis, such that if the optical signal passes out of the acceptable range, an alarm is sounded. Most preferably, analysis engine **332** is able to include an estimate of optical attenuation caused by the optical switch, for a more accurate determination of the power level of the optical signal.

While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

WHAT IS CLAIMED IS:

1. A device for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, comprising:

(a) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled.

2. The device of claim 1, further comprising:

(b) for each wavelength, a mechanism for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths.

3. The device of claim 2, wherein said mechanism includes a filter.

4. The device of claim 3, wherein each said electroholographic switches includes at least one photorefractive crystal including a grating specific to said wavelength that is switched by said each electroholographic switch.

5. The device of claim 4, wherein said grating is stored in said crystal as a hologram.

6. The device of claim 4, wherein said photorefractive crystal includes a photorefractive material selected from the group consisting of potassium tantalate niobate, strontium barium niobate and potassium lithium tantalate niobate.

7. The device of claim 6, wherein said photorefractive crystal includes potassium lithium tantalate niobate doped with copper and vanadium.

8. The device of claim 4, wherein each said grating effects said switching at an angle substantially equal to 90°.

9. The device of claim 1, further comprising:

(b) for each of at least a portion of the wavelengths, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits.

10. The device of claim 9, wherein said detector further comprises:

(i) a switch interface for connecting to said electroholographic switch and for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits; and

(ii) an analyzer for receiving an optical signal from said switch interface according to the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits and for converting said optical signal to a voltage for analysis.

11. The device of claim 10, wherein said analyzer further comprises:

(1) a photo-detector for receiving said optical signal from said switch interface and for converting said optical signal to said voltage;

(2) a high threshold voltage comparator for comparing said voltage to a high voltage threshold, such that if said voltage is higher than said high voltage threshold, a high voltage indication is indicated; and

(3) a low threshold voltage comparator for comparing said voltage to a low voltage threshold, such that if said voltage is lower than said low voltage threshold, a low voltage indication is indicated.

12. The device of claim 11, wherein at least one of said low voltage indication and said high voltage indication is an LED.

13. The device of claim 12, wherein the device is in communication with a host and wherein the device further comprises a host interface for transmitting information to said host, such that at least one of said low voltage indication and said high voltage indication is an alarm indication for transmitting to said host.

14. The device of claim 10, wherein the device is in communication with a host and wherein the device further comprises a host interface for transmitting information to said host, and wherein said analyzer further comprises:

(1) a transistor for receiving the optical signal from said switch interface and for converting the optical signal to said voltage; and

(2) an analog to digital (A/D) converter for converting said voltage to a digital signal and for transmitting said digital signal to said host through said host interface.

15. The device of claim 14, wherein said A/D converter transmits said digital signal to said host upon receiving a request from said host through said host interface.

16. The device of claim 9, wherein said detector further comprises:

(i) a switch interface for connecting to said electroholographic switch and for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits; and

(ii) a management analyzer for analyzing at least one wavelength of the optical signal to determine a quality of the optical signal.

17. The device of claim 16, wherein said optical signal is comprised of a plurality of wavelengths and said detector further comprises an electroholographic switch for switching one of said plurality of wavelengths of said optical signal to said management analyzer.

18. The device of claim 17, wherein said management analyzer further comprises:

(1) at least one receiver for receiving a single wavelength of said optical signal and for converting said single wavelength of said optical signal to a digital signal; and

(2) an analysis engine for analyzing said digital signal to determine said quality of said optical signal.

19. The device of claim 18, wherein said digital signal from said receiver is a serial digital signal and said management analyzer further comprises:

(3) a data translator for translating said serial digital signal to a parallel digital signal, and for passing said parallel digital signal to said analysis engine.

20. The device of claim 17, wherein said management analyzer further comprises:

(1) an optical signal wavelength selector for selecting a wavelength of said optical signal;

(2) a single receiver for receiving said wavelength of said optical signal and for converting said wavelength of said optical signal to a digital signal; and

(3) an analysis engine for analyzing said digital signal to determine said quality of said optical signal.

21. The device of claim 20, wherein said management analyzer further comprises:

(4) a photo-detector for monitoring a power of said optical signal from said optical signal wavelength selector.

22. The device of claim 20, wherein said optical signal wavelength selector is an electroholographic switch.

23. The device of claim 1, further comprising:

(b) for each wavelength, a mechanism for diverting, to an uplink conduit, the light of said each wavelength remaining after said controllable portion of the light of said each wavelength is switched to the output conduits.

24. The device of claim 23, wherein said mechanism for diverting said remaining light to said uplink conduit includes an electroholographic switch.

25. The device of claim 1, wherein at least one of said output conduits includes a transponder for receiving said controllable portions of the light that is switched to said at least one output conduit and emitting corresponding light of a single output wavelength.

26. The device of claim 1, further comprising:

(b) for each of at least a portion of the output conduits:

(i) a detector; and

(ii) a mechanism for diverting, to said detector, a subportion of each said controllable portion of the light that is switched to said each output conduit.

27. The device of claim 26, wherein said mechanism for diverting said subportion includes a component selected from the group consisting of beamsplitters and electroholographic switches.

28. The device of claim 1, further comprising:

(b) for each of at least a portion of said wavelengths:

(i) a light source emitting light of a wavelength other than said each wavelength; and

(ii) for each said output conduit, a detector for receiving said light of said other wavelength from said

electroholographic switch that switches said controllable portion of said light of said each wavelength to said each output conduit.

29. A method for switching light of any of a plurality of discrete wavelengths to any of a plurality of output conduits, comprising the steps of:

(a) providing, for each wavelength and for each output conduit, a respective electroholographic switch;

(b) for each wavelength, diverting the light of said each wavelength to said electroholographic switches of said each wavelength; and

(c) for each said electroholographic switch, setting a state of said each switch so as to further divert a desired portion of the light of said respective wavelength of said each switch to said respective output conduit of said each switch.

30. The method of claim 29, wherein said setting of said state of said each switch is effected by applying to said each switch a voltage effective to further divert said desired portion of the light of said respective wavelength of said each switch to said respective output conduit of said each switch.

31. The method of claim 29, further comprising the steps of:

(d) for each wavelength, measuring an intensity of the light of said each wavelength remaining after said desired portions of the light of said each wavelength are diverted to the output conduits; and

(e) adjusting said voltages based on said measured intensities.

32. The method of claim 29, further comprising the step of:

(d) for each output conduit, verifying that said desired portion of each wavelength has been diverted to said each output conduit.

33. The method of claim 32, wherein said verifying is effected by steps including, for each output conduit:

(i) diverting a subportion of each said desired portion of the light that is diverted to said each output conduit; and

(ii) measuring an intensity of said subportion.

34. The method of claim 32, wherein said verifying is effected by steps including, for each wavelength:

(i) directing light of a wavelength other than said each wavelength at said respective electroholographic switches; and

(ii) for each output conduit, measuring an intensity of said light of said wavelength other than said each wavelength that is diverted by said respective electroholographic switch.

35. A device for switching light of any of a plurality of discrete wavelengths to any of a first and second pluralities of output conduits, comprising:

(a) a first module including:

(i) for each wavelength and for each output conduit of the first plurality, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit of the first plurality, said electroholographic switches of a common output conduit of the first plurality being optically coupled, said electroholographic switches of a common wavelength being optically coupled; and

(b) a second module including:

(i) for each wavelength and for each output conduit of the second plurality, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit of the second plurality, said electroholographic switches of a common output conduit of the second plurality being optically coupled, said electroholographic switches of a common wavelength being optically coupled.

36. The device of claim 35, wherein said first module further includes:

(ii) for each wavelength, a mechanism for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths;

37. The device of claim 35, wherein, for each said wavelength, said respective electroholographic switches of said second module are optically coupled to said respective electroholographic switches of said first module.

38. A device for switching light of any of a first and second pluralities of discrete wavelengths to any of a first and second pluralities of output conduits, comprising:

(a) an uplink conduit;

(b) a first module including:

(i) for each wavelength of the first plurality of wavelengths and for each output conduit of the first plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and

(ii) for each wavelength of the first plurality, a mechanism for diverting, to said uplink conduit, the light of said each wavelength remaining after said controllable portion of the light of said each wavelength is switched to the first plurality of output conduits; and

(c) a second module including:

(i) for each wavelength of the second plurality of wavelengths and for each output conduit of the second plurality of output conduits, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said

each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and

(ii) for each wavelength of the second plurality, a mechanism, optically coupled to said uplink conduit, for diverting the light of said each wavelength to said respective electroholographic switches while passing the light of all other wavelengths.

39. A device for switching light of any of a first and second pluralities of discrete wavelengths to any of a plurality of output conduits, comprising:

(a) a first module including:

(i) for each wavelength of the first plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the first plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the first plurality being optically coupled; and

(b) a second module including:

(i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the second plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the second plurality being optically coupled.

40. The device of claim 39, wherein each said module further includes, for

each wavelength of the respective plurality:

(ii) a mechanism for diverting the light of said each wavelength of said respective plurality to said respective electroholographic switches while passing the light of all other wavelengths.

41. The device of claim 39, wherein, for each output conduit, said respective electroholographic switches of said first module are optically coupled to said respective electroholographic switches of said second module.

42. The device of claim 39, further comprising:

(c) an uplink conduit;

and wherein each said module further includes, for each wavelength of the respective plurality:

(iii) a mechanism for diverting, to said uplink conduit, the light of said each wavelength of said respective plurality remaining after said controllable portion of the light of said each wavelength of said respective plurality is switched to the output conduits.

43. A device for switching light of any of a plurality of discrete wavelengths from at least one of a plurality of input conduits to any one of a plurality of output conduits, comprising:

(a) for each input conduit, a module including:

(i) for each wavelength and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength being optically coupled, and

(ii) for each wavelength, a mechanism for diverting the light of said each wavelength from said each input conduit to said respective electroholographic switches while passing the light of all other

wavelengths; and

(b) for each output conduit, a multiplexer for combining outputs of all said respective electroholographic switches into said each output conduit.

44. A device for converting light of any of a first plurality of discrete wavelengths to light of any of a second plurality of discrete wavelengths, said first and second pluralities being equal in number, and then switching the light of the second plurality of discrete wavelengths to any of a plurality of output conduits, comprising:

(a) a first module including:

(i) a plurality of transponders, equal in number to the first plurality of wavelengths, each said transponder outputting light of a respective wavelength of the second plurality, and

(ii) for each wavelength of the first plurality and for each transponder, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the first plurality to said each transponder, said electroholographic switches of a common transponder being optically coupled, said electroholographic switches of a common wavelength of the first plurality being optically coupled; and

(b) a second module including:

(i) for each wavelength of the second plurality and for each output conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the second plurality to said each output conduit, said electroholographic switches of a common output conduit being optically coupled, said electroholographic switches of a common wavelength of the second plurality being optically coupled.

45. The device of claim 44, wherein said first module further includes, for each wavelength of the first plurality:

(iii) a mechanism for diverting the light of said each wavelength of the first plurality to said respective electroholographic switches while passing the light of all other wavelengths.

46. The device of claim 44, wherein said first module further includes:

(iii) for each of at least a portion of the wavelengths of the first plurality, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the transponders.

47. The device of claim 46, wherein said second module further includes:

(ii) for each of at least a portion of the wavelengths of the second plurality, a detector for receiving the light of said each wavelength remaining after said controllable portions of the light of said each wavelength is switched to the output conduits.

48. In an optical communication system wherein signals are carried in a plurality of channels, each channel including light of a respective discrete wavelength, an add-drop multiplexer, for replacing at least one input signal with a corresponding at least one output signal on a respective subplurality of the channels, comprising:

(a) an uplink conduit;

(b) a drop module including:

(i) a plurality of diversion conduits,

(ii) for each wavelength of the subplurality and for each said diversion conduit, an electroholographic switch for switching a controllable portion of the light of said each wavelength of the subplurality to said each diversion conduit, said electroholographic switches of a common diversion conduit being optically coupled, said electroholographic switches of a common wavelength of the subplurality being optically coupled, and

(iii) a mechanism for diverting the light of said each wavelength of said subplurality to said respective electroholographic switches while passing the light of all other wavelengths to said uplink conduit; and

(c) an add module including:

(i) a plurality of substitution conduits, and

(ii) a mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink conduit.

49. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one y-junction for each said substitution conduit.

50. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one wide-band switch for each said substitution conduit.

51. The add-drop multiplexer of claim 48, wherein said mechanism for diverting light of the wavelengths of the subplurality from each said substitution conduit to said uplink includes one electroholographic switch for each said substitution conduit.

52. In an optical communications system wherein signals are carried in a plurality of channels via a common conduit, each channel having a respective discrete wavelength, a device for tapping the channels, comprising:

(a) for each channel, a respective electroholographic switch for diverting a controllable portion of said signals of said each channel from the common conduit.

53. The device of claim 52, further comprising:

(b) for each channel, a mechanism for measuring an intensity of said controllable portion of said signals of said each channel.

54. The device of claim 53, further comprising:

(c) an amplifier, upstream from said electroholographic switches, for amplifying the intensities of the channels; and

(d) a mechanism, upstream of said amplifier, for adjusting the intensities of the channels, based on said measured intensities of said controllable portions of said signals.

55. An electroholographic switch, for switching light of a certain wavelength, comprising:

(a) a crystal of a photorefractive material including a plurality of electroholographic gratings, said electroholographic gratings being spaced apart laterally within said crystal; and

(b) for each said electroholographic grating, two electrodes for activating said each grating.

56. The device of claim 55, wherein said photorefractive material is selected from the group consisting of potassium tantalate niobate, strontium barium niobate and potassium lithium tantalate niobate.

57. An optical switch comprising a paraelectric photorefractive material, wherein is stored a plurality of superposed holograms whose reconstruction is controllable by means of an applied electric field.

58. A method for determining a level of amplification of an optical signal for switching the optical signal to a primary output conduit, the method comprising the steps of:

(a) providing at least one electroholographic switch for switching the optical signal to the primary output conduit;

(b) diverting a first portion of the optical signal through said electroholographic switch to the primary output conduit and a second portion of the optical signal through said electroholographic switch to a secondary output conduit;

(c) detecting a power of said second portion; and

(d) based on said detected power of said second portion, adjusting a power of said first portion.

59. The method of claim 58, wherein said adjusting of said power of said first portion is effected by applying a corresponding voltage to each of said at least one electroholographic switch.

60. The method of claim 58, wherein the optical signal comprises a plurality of wavelengths, each of said plurality of wavelengths being switched by a respective electroholographic switch to a respective primary output conduit.

61. A method for analyzing at least one quality characteristic of an optical signal, the method comprising the steps of:

(a) providing an electroholographic switch for diverting at least a portion of the optical signal for analysis;

(b) diverting said at least a portion of the optical signal for analysis; and

(c) analyzing said at least a portion of the optical signal to determine the at least one quality characteristic.

62. The method of claim 61, wherein said at least one quality characteristic is a saturation of a level of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

(i) converting said at least a portion of the optical signal to a voltage;

(ii) comparing said voltage to a maximum preset high threshold; and

(iii) if said voltage is greater than said maximum preset high threshold, determining that said level of the optical signal to said

electroholographic switch is saturated.

63. The method of claim 61, wherein said at least one quality characteristic is a low level of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

(i) converting said at least a portion of the optical signal to a voltage;

(ii) comparing said voltage to a minimum preset low threshold; and

(iii) if said voltage is less than said minimum preset low threshold, determining that said level of the optical signal to said electroholographic switch is at said low level.

64. The method of claim 61, wherein said at least one quality characteristic is a power of the optical signal to said electroholographic switch, wherein step (c) further comprises the steps of:

(i) converting said at least a portion of the optical signal to a voltage;

(ii) converting said voltage to a digital signal; and

(iii) determining said power of the optical signal from said digital signal.

65. The method of claim 61, wherein said at least one quality characteristic is an attenuation of the optical signal.

66. The method of claim 61, wherein the optical signal comprises a plurality of wavelengths, and step (a) further comprises the step of providing a plurality of electroholographic switches, each of said plurality of electroholographic switches being dedicated to one of said plurality of wavelengths, such that steps (b) and (c) are performed for each of said plurality of wavelengths.

67. The method of claim 66, wherein steps (b) and (c) are performed sequentially for each of said plurality of wavelengths.

68. The method of claim 66, wherein steps (b) and (c) are performed

substantially simultaneously for at least two of said plurality of wavelengths.

69. A method of communication wherein optical signals are transmitted through an optical communication network, the optical signals being encoded in a plurality of channels propagating in an optical medium, the method comprising the steps of:

(a) diverting only a portion of the optical signals in each channel while a remainder of the optical signals in each channel continues to propagate in the optical medium;

(b) converting each portion to an electronic signal; and

(c) managing the network in accordance with said electronic signal.

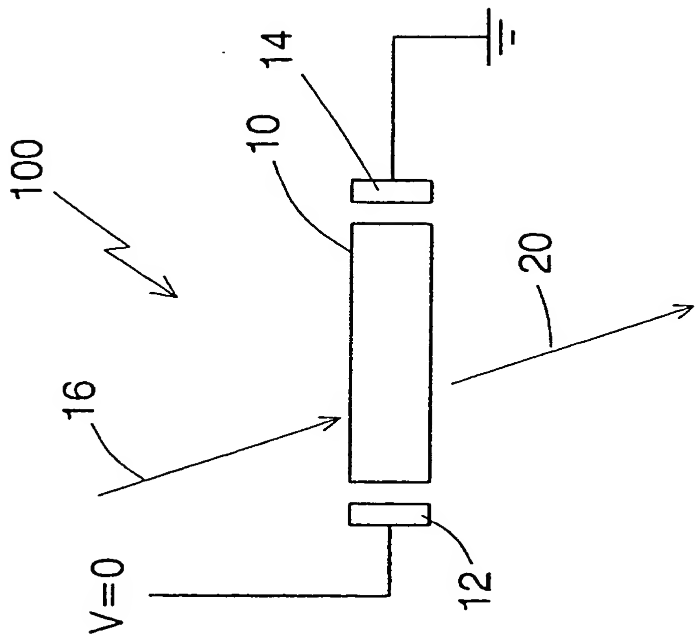

FIG. 1B
(PRIOR ART)

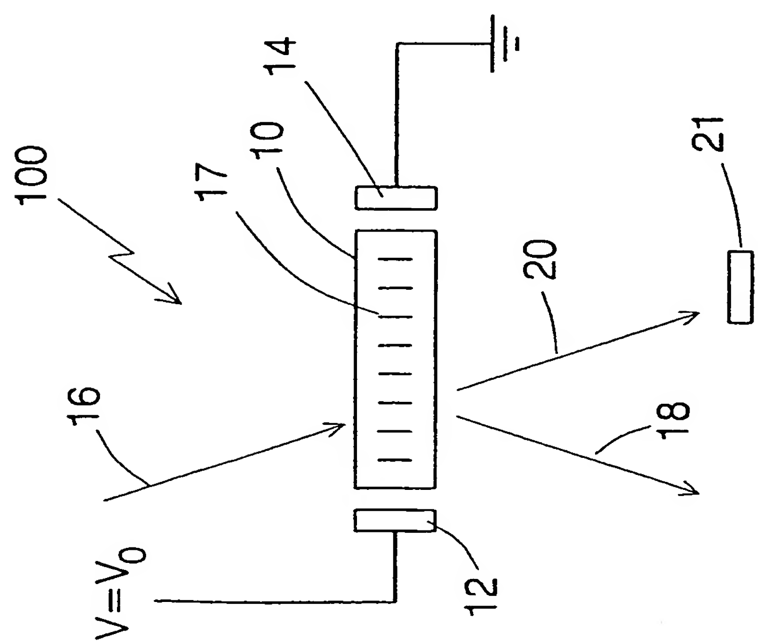

FIG. 1A
(PRIOR ART)

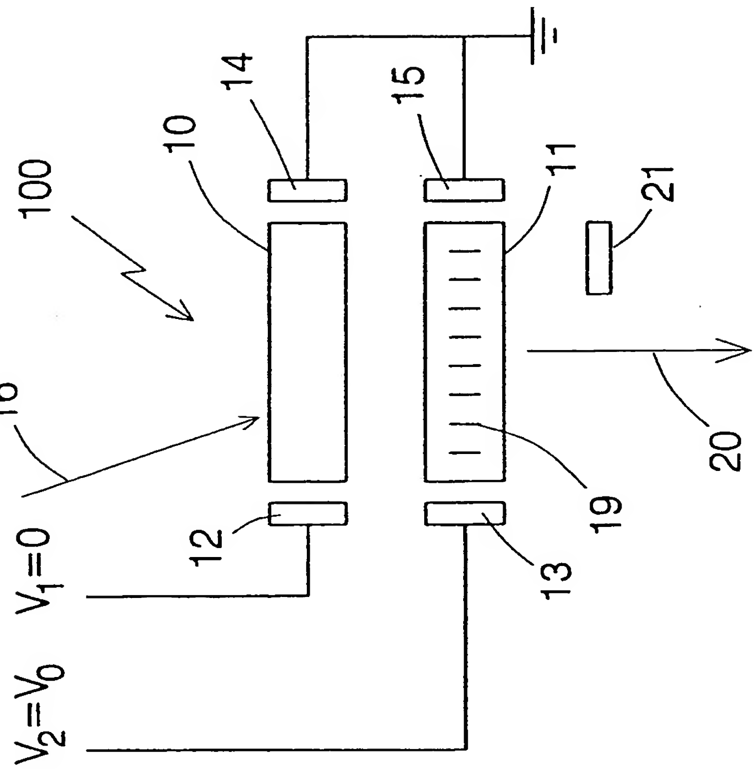

FIG. 1D
(PRIOR ART)

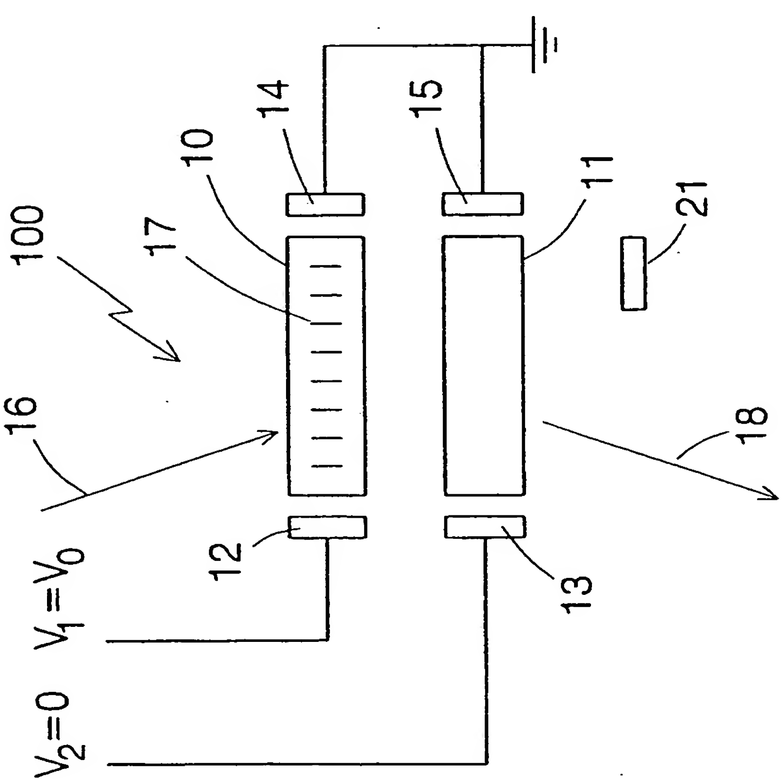

FIG. 1C
(PRIOR ART)

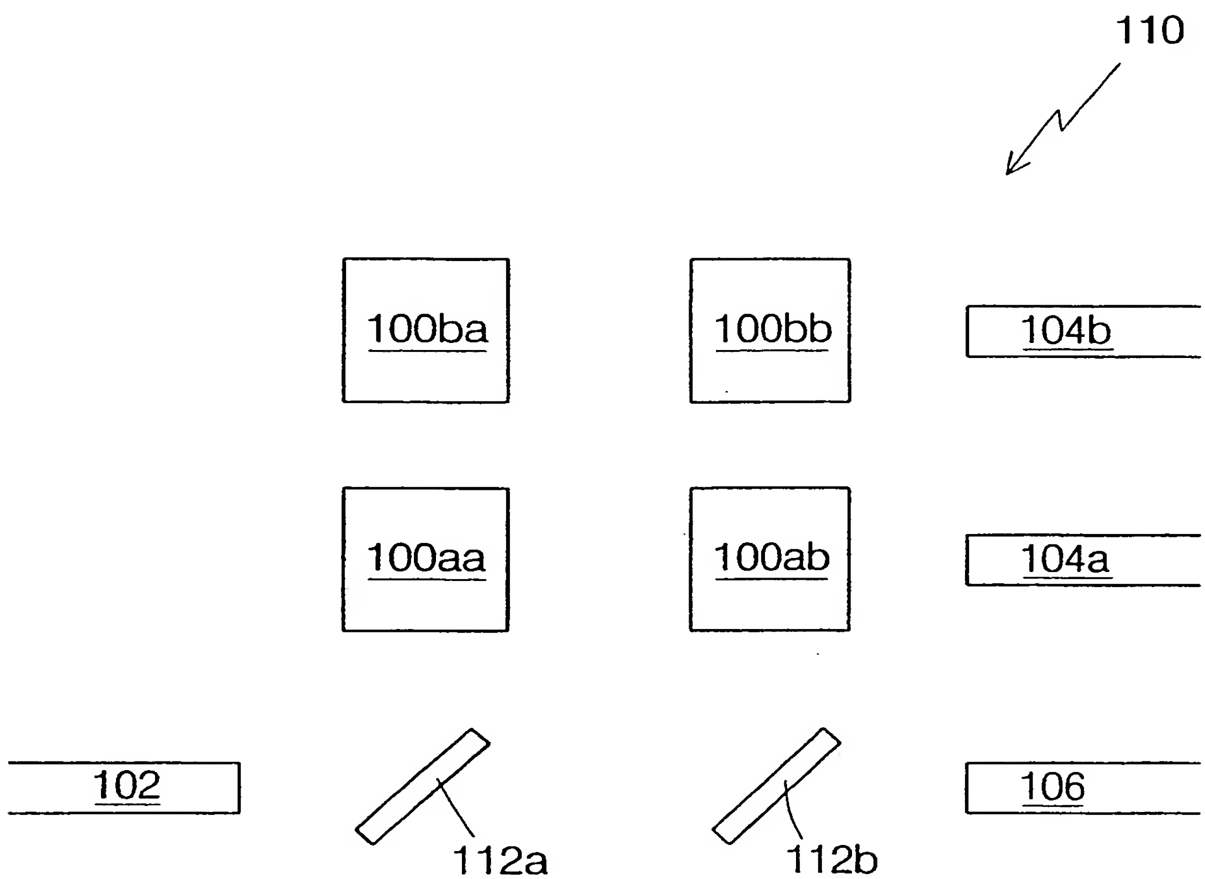

FIG. 2

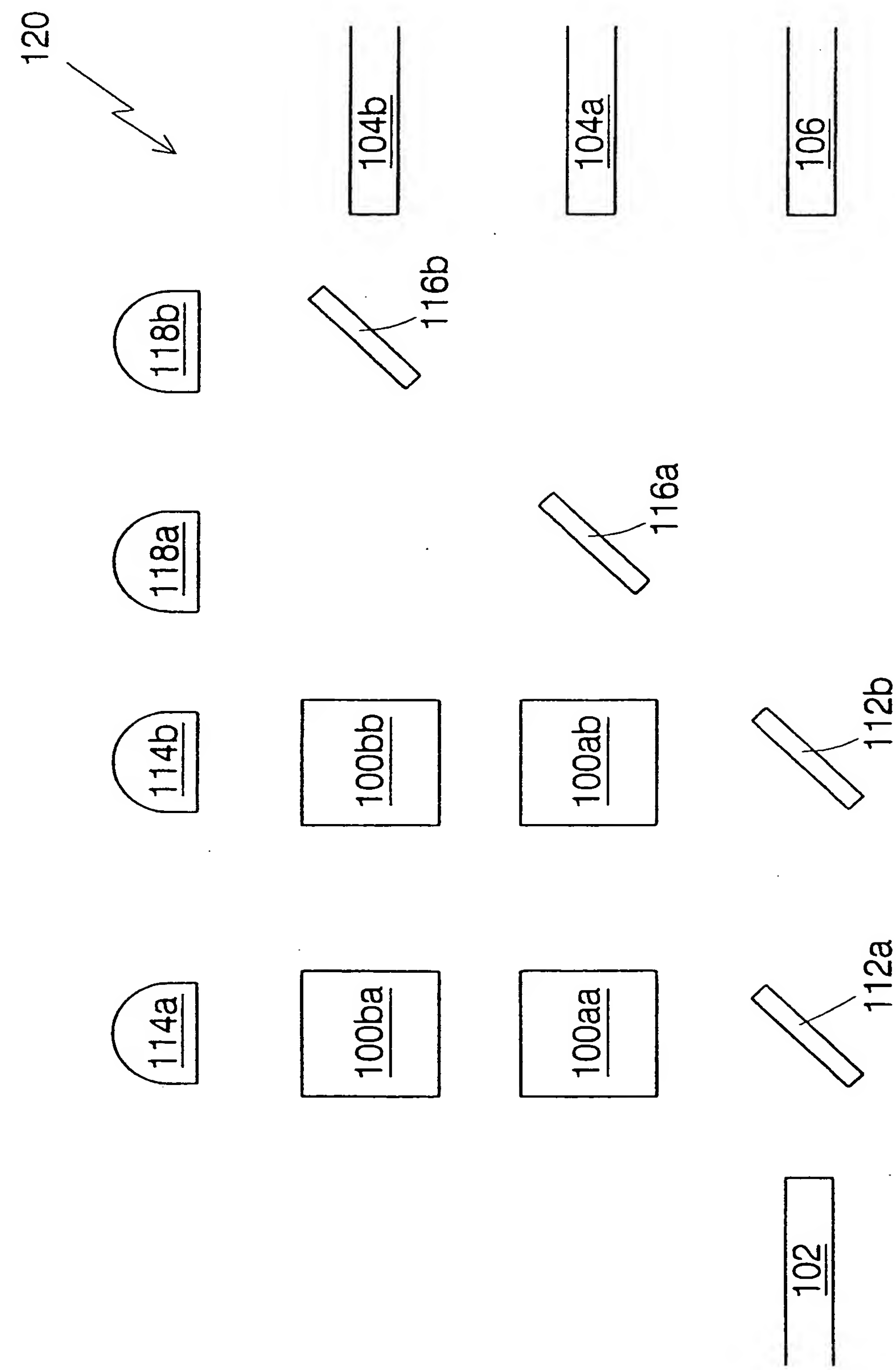
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FIG. 3

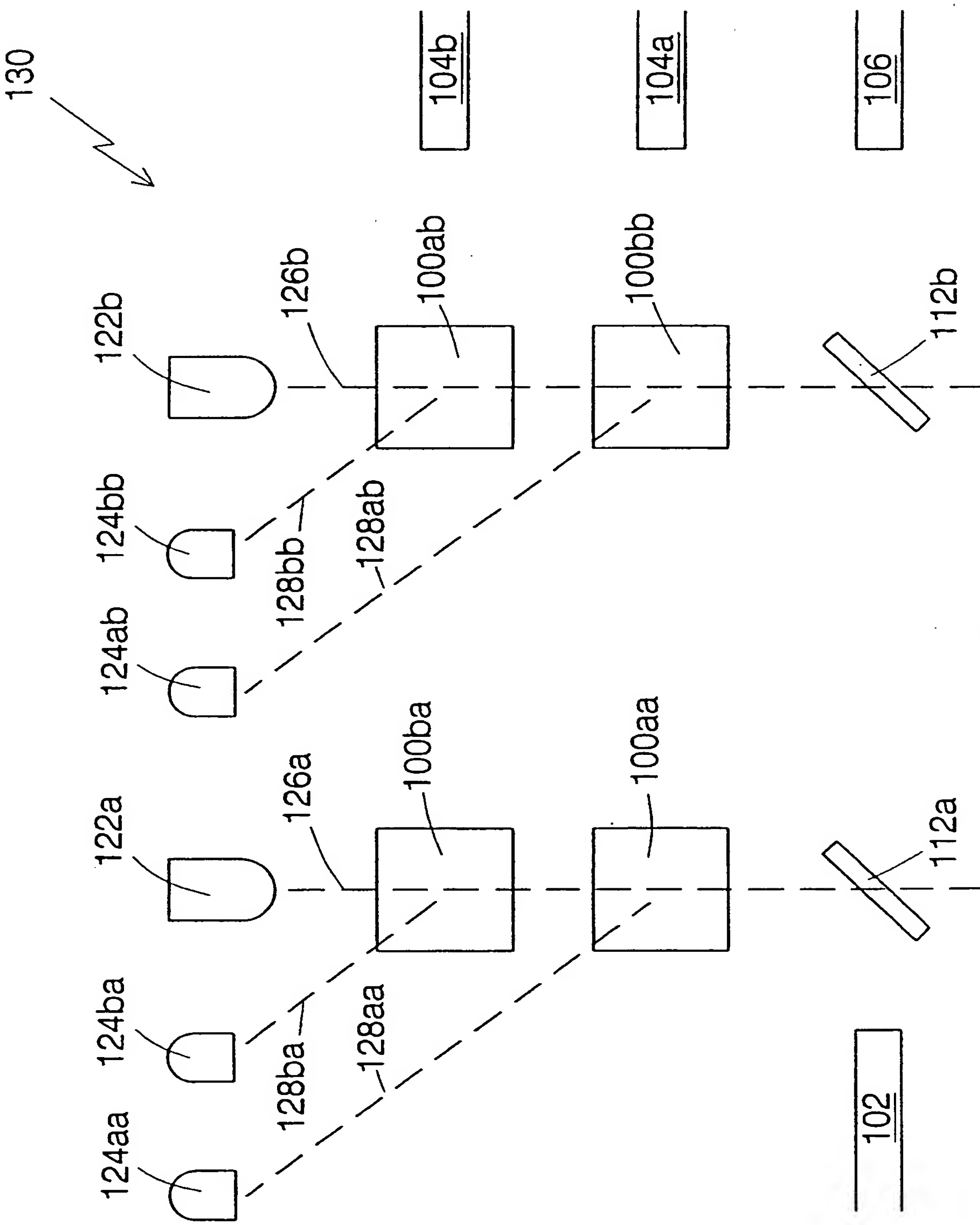
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FIG. 4

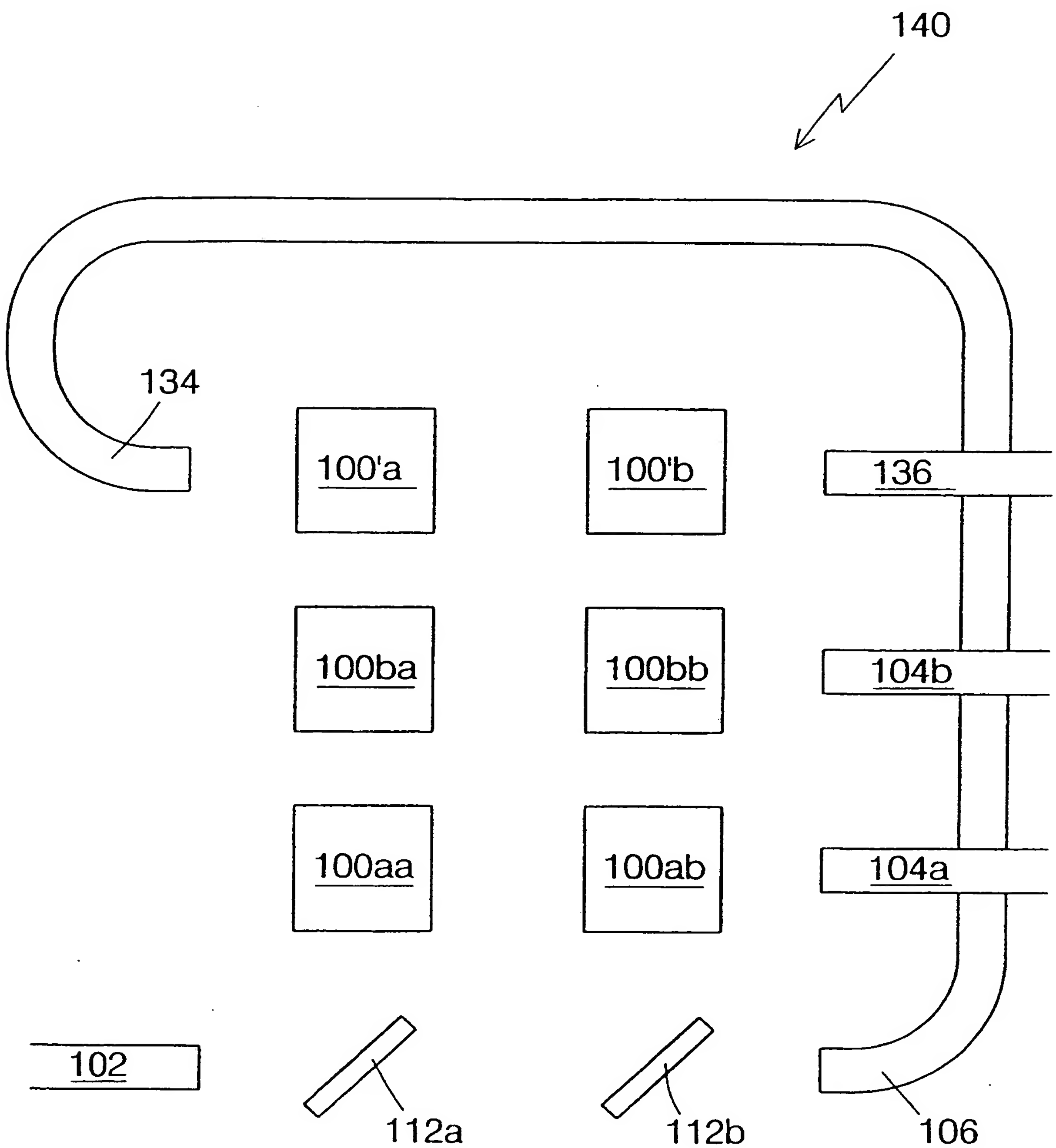
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FIG. 5

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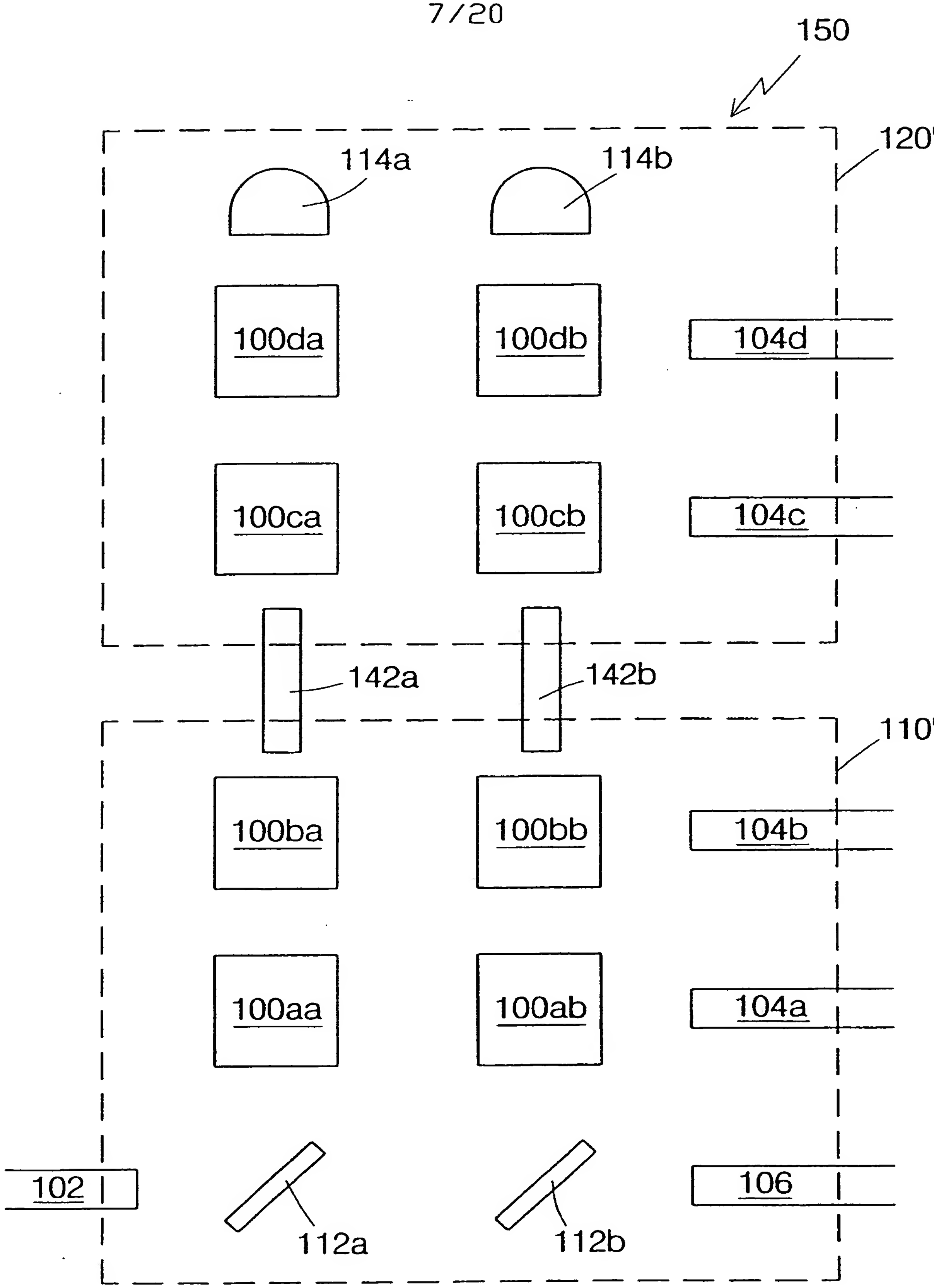
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FIG.6

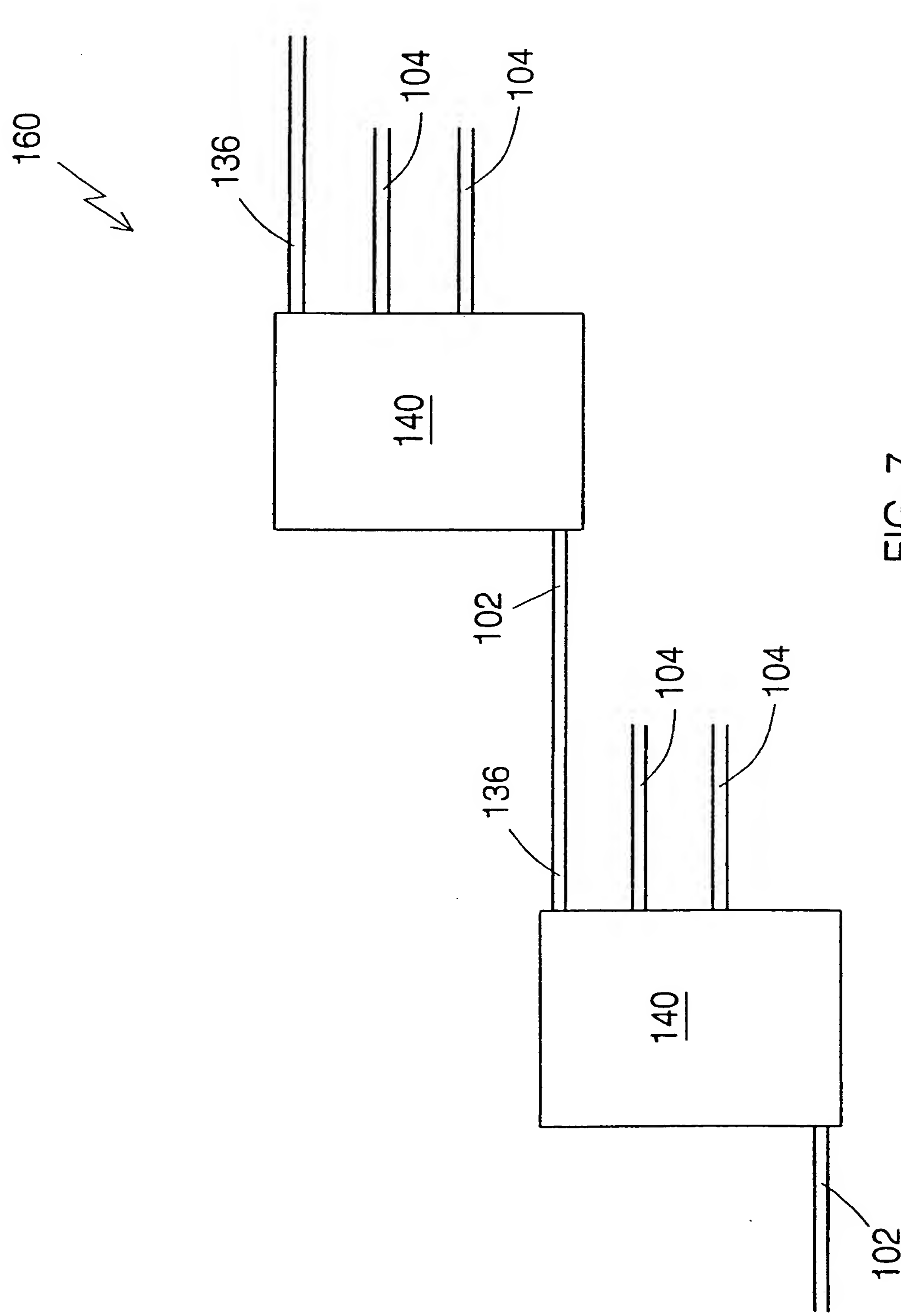

FIG. 7

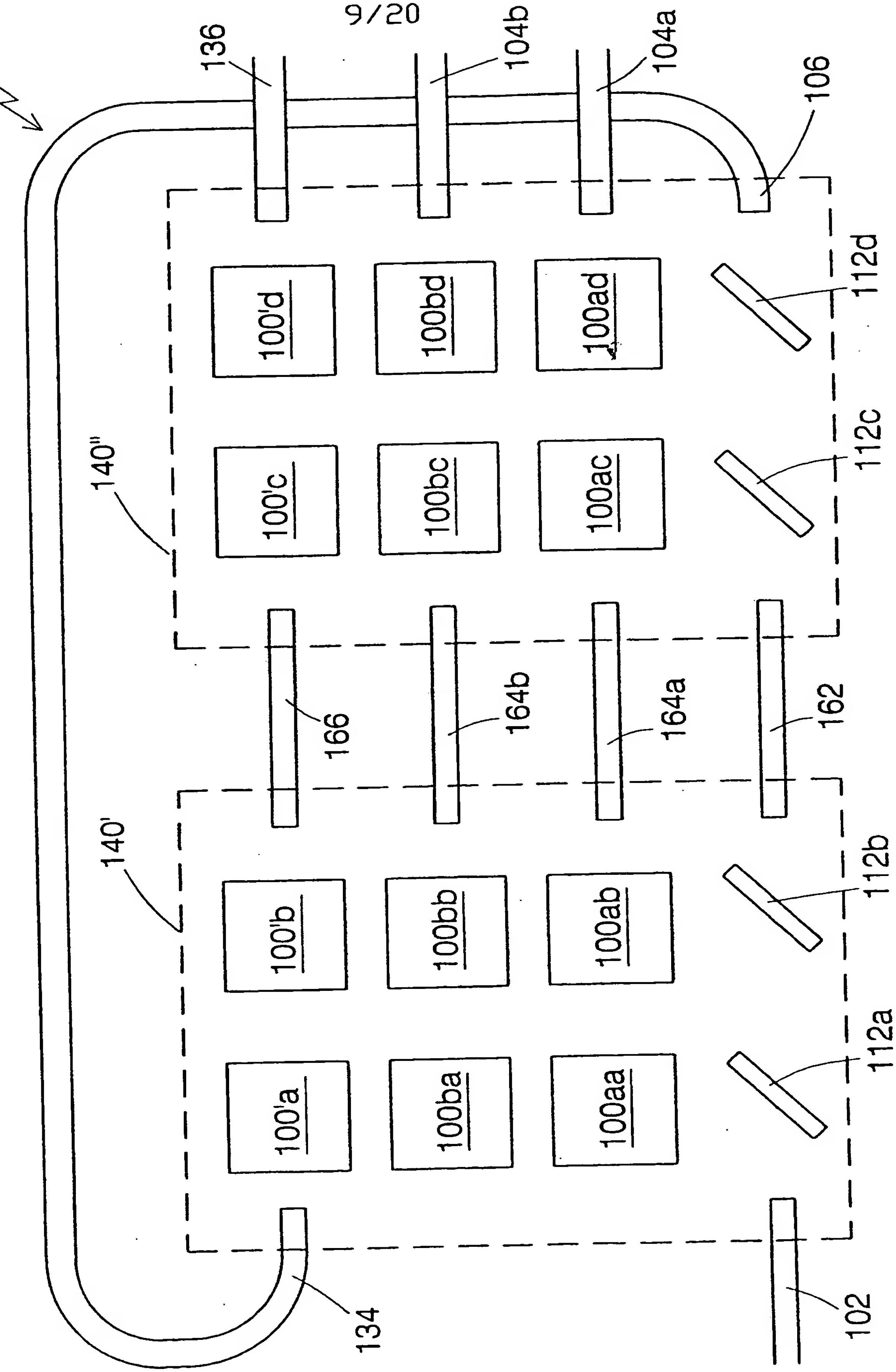
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FIG. 8

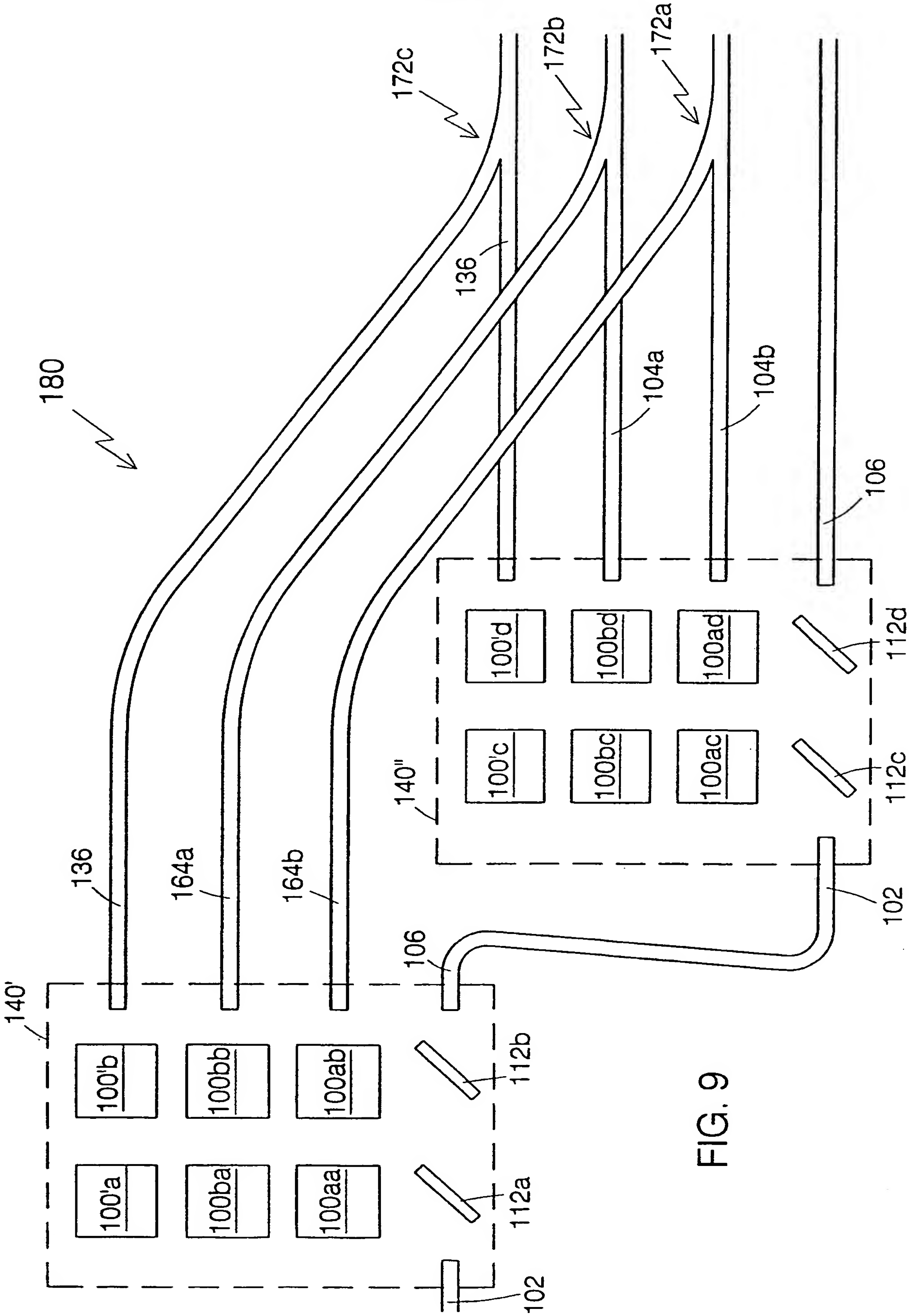
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FIG. 9

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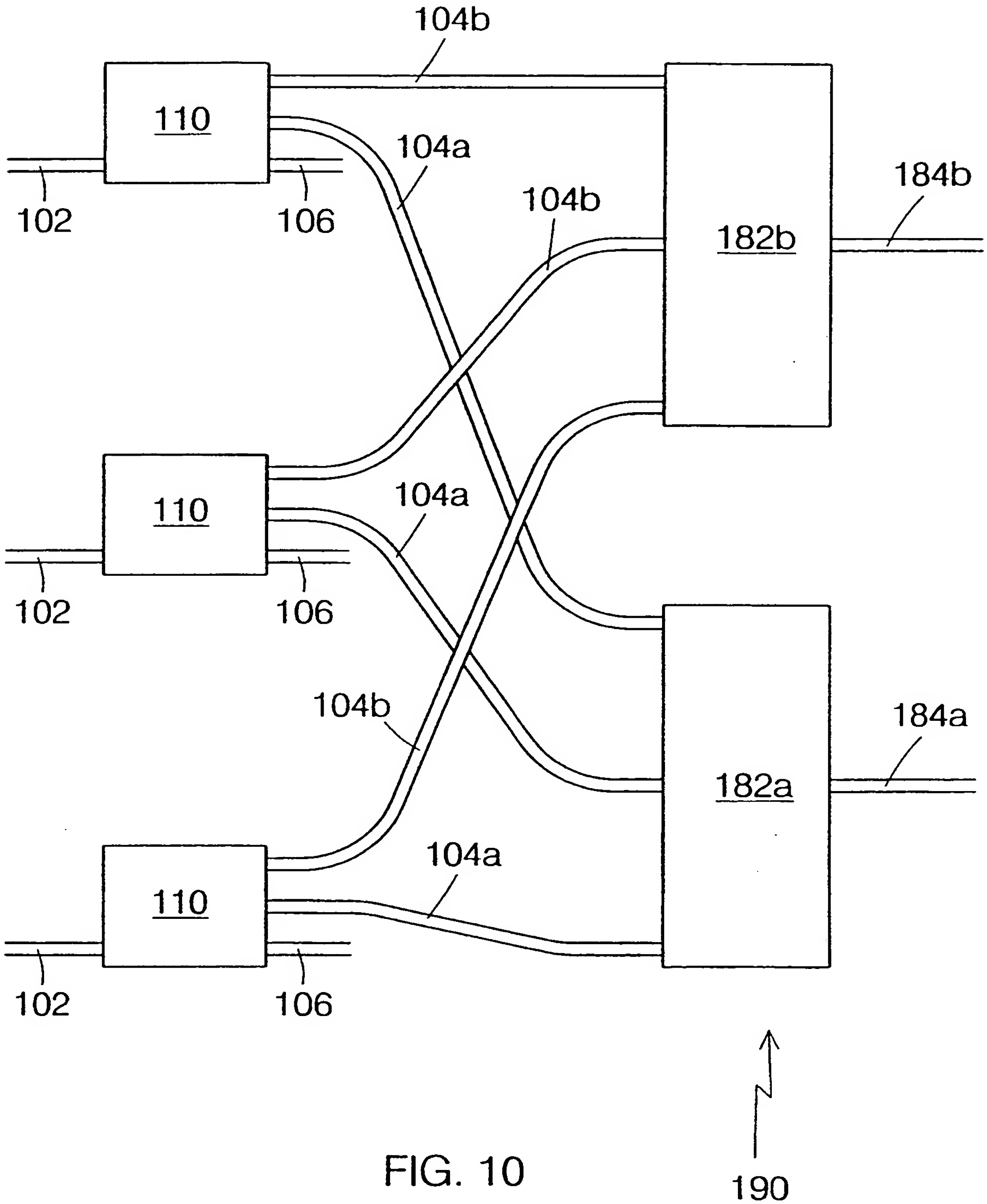
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FIG. 10

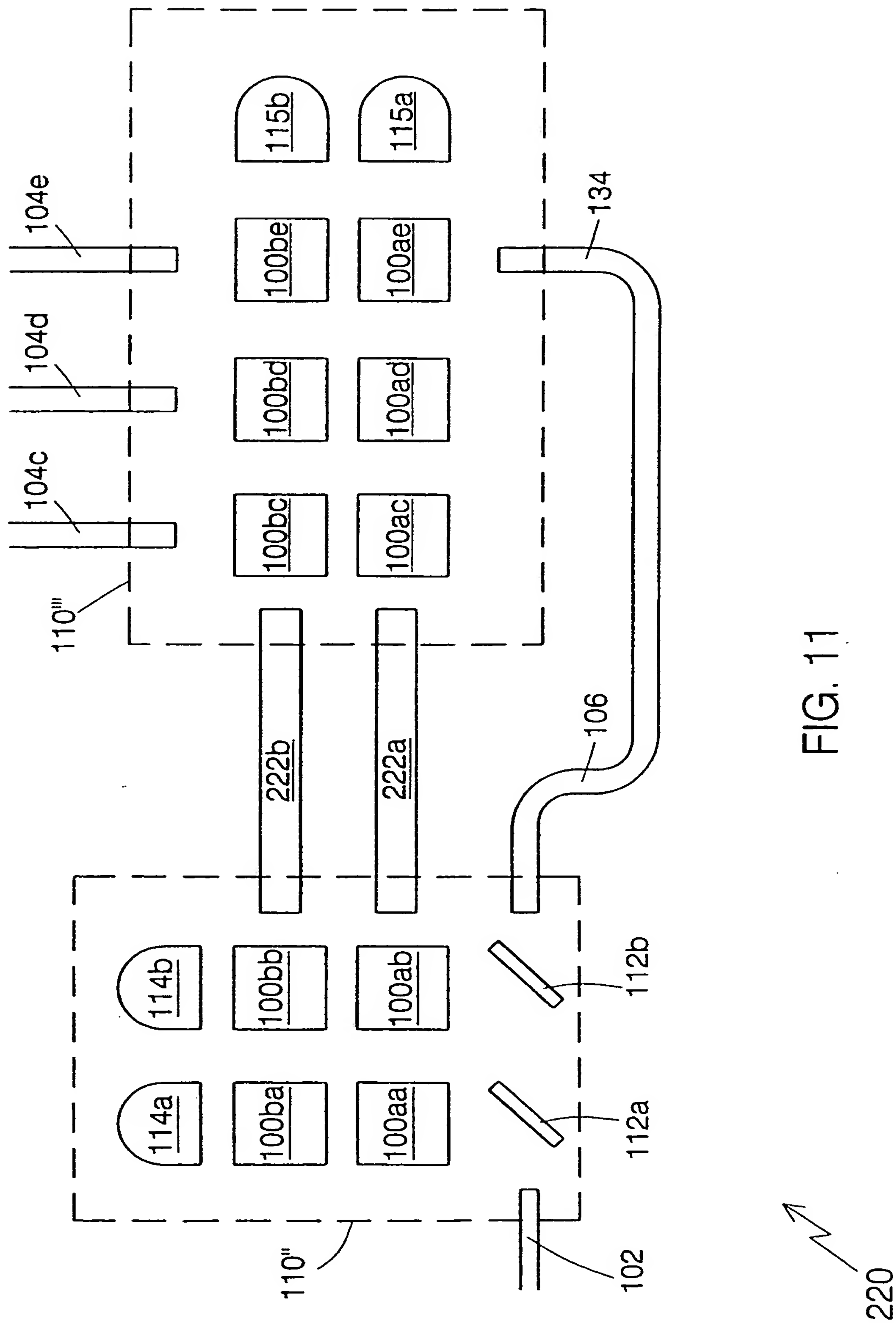
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FIG. 11

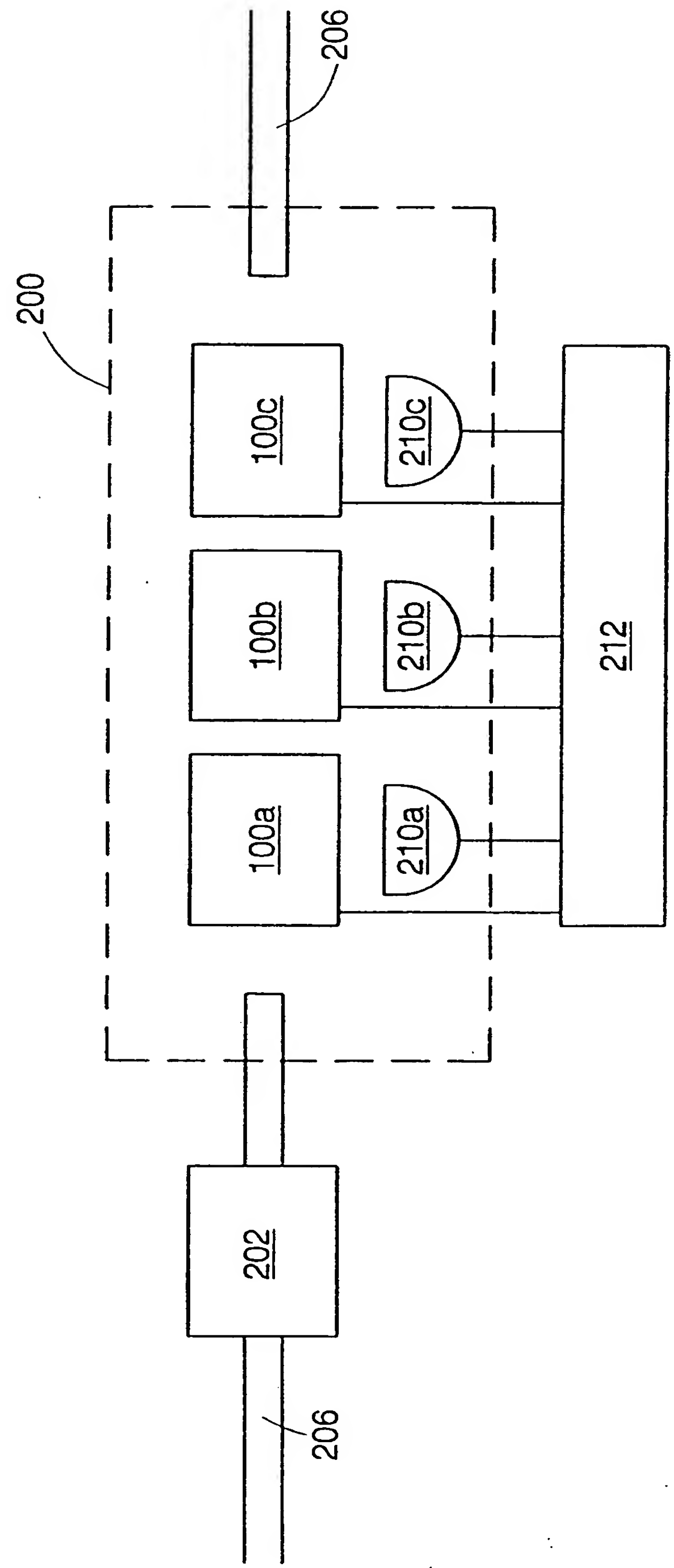

FIG. 12

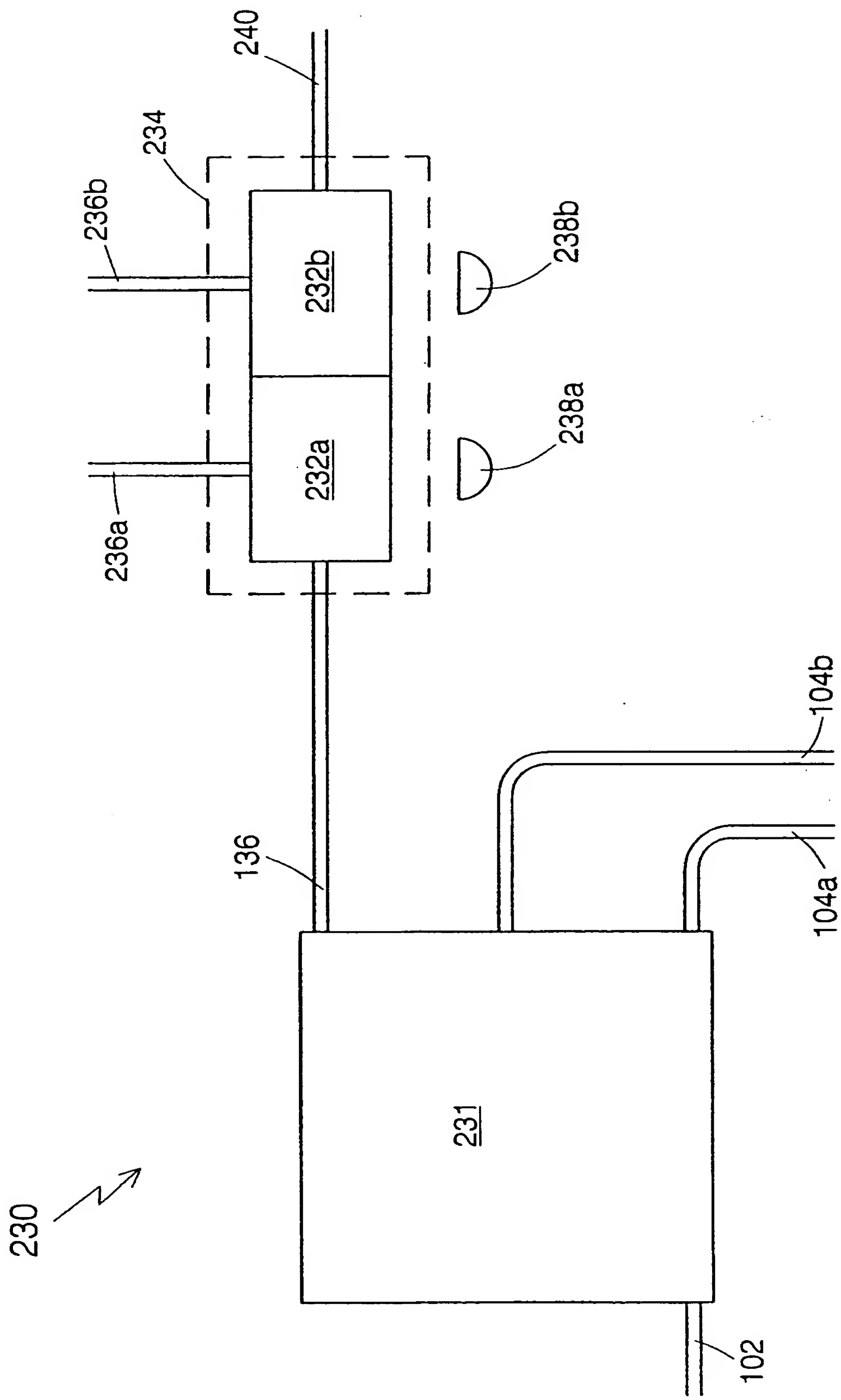
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FIG. 13

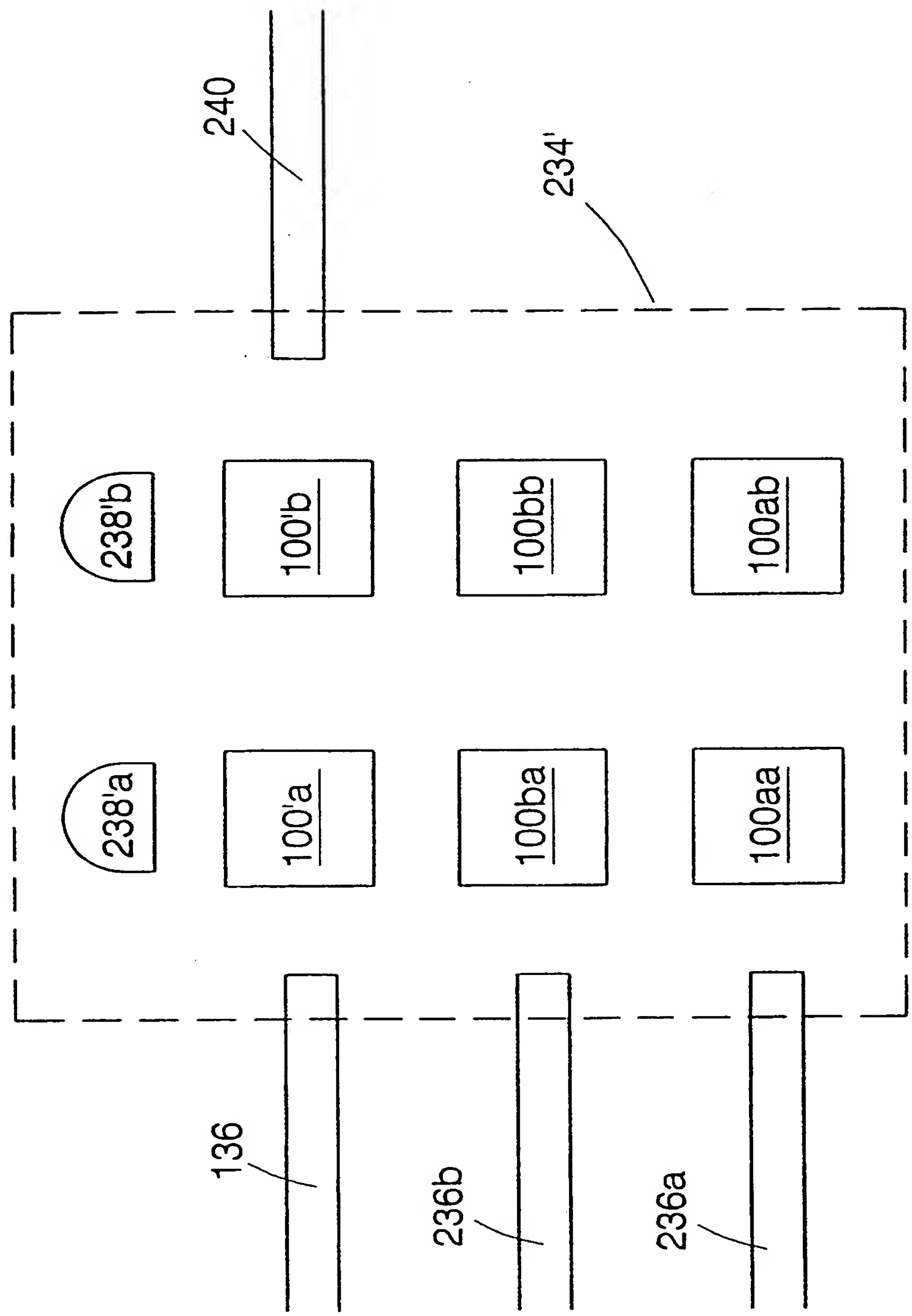
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FIG. 14

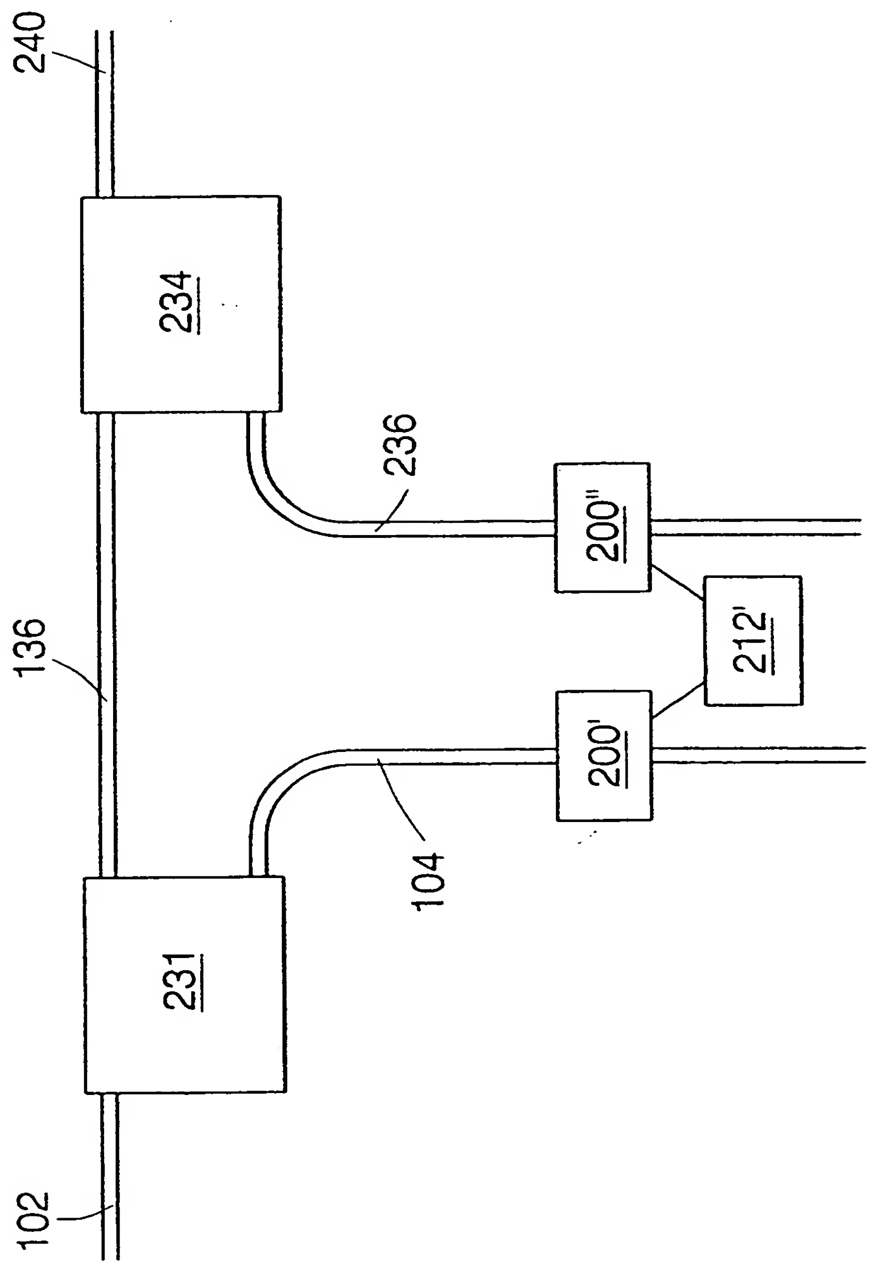

FIG. 15

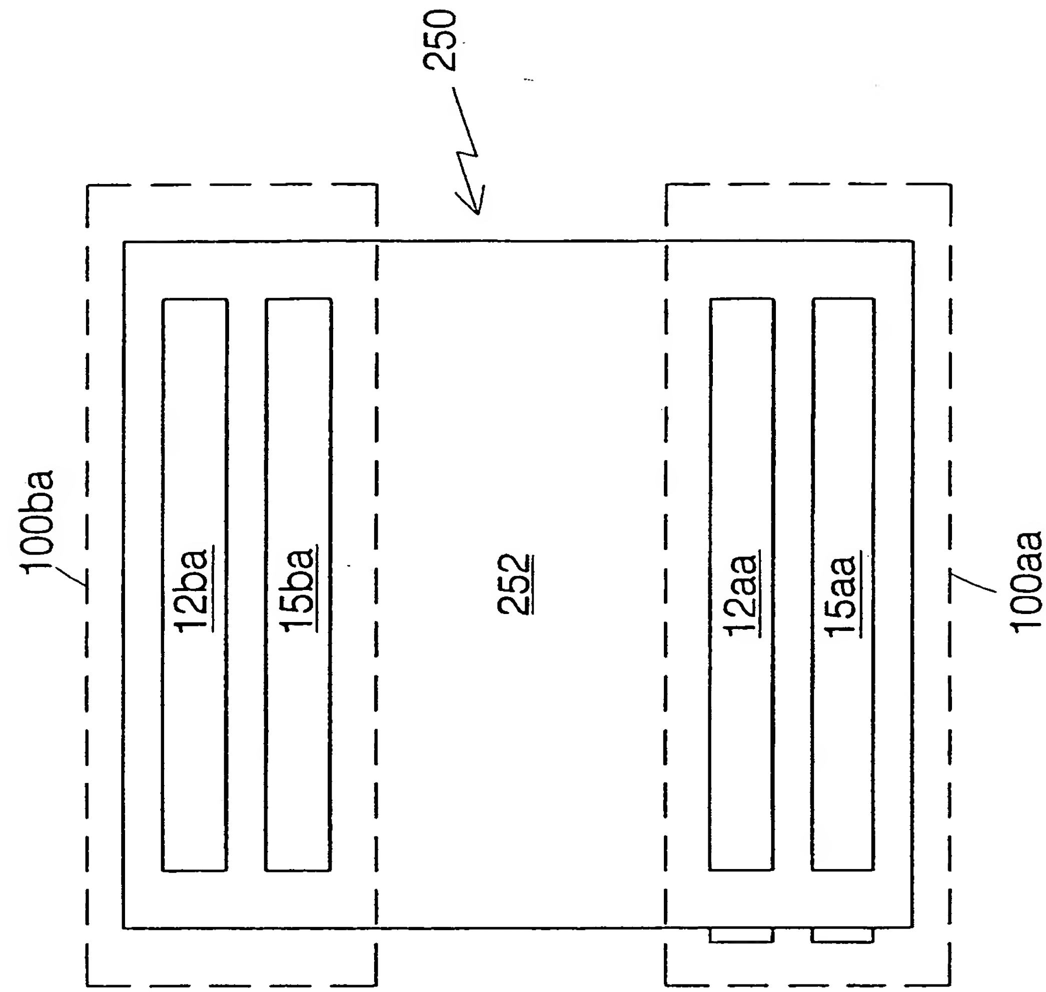

FIG. 16B

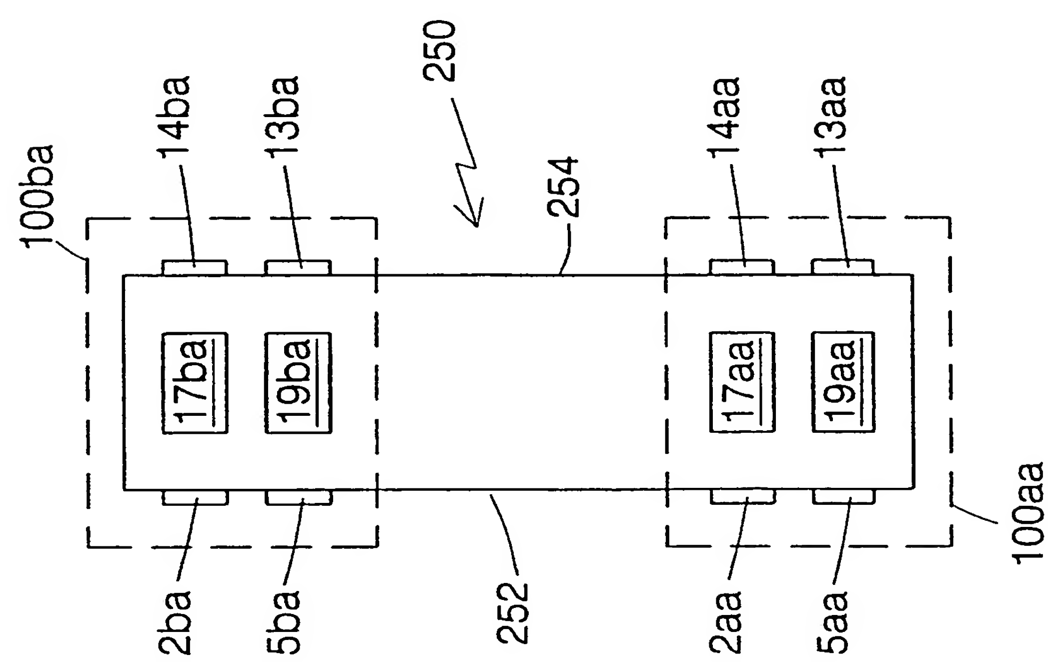

FIG. 16A

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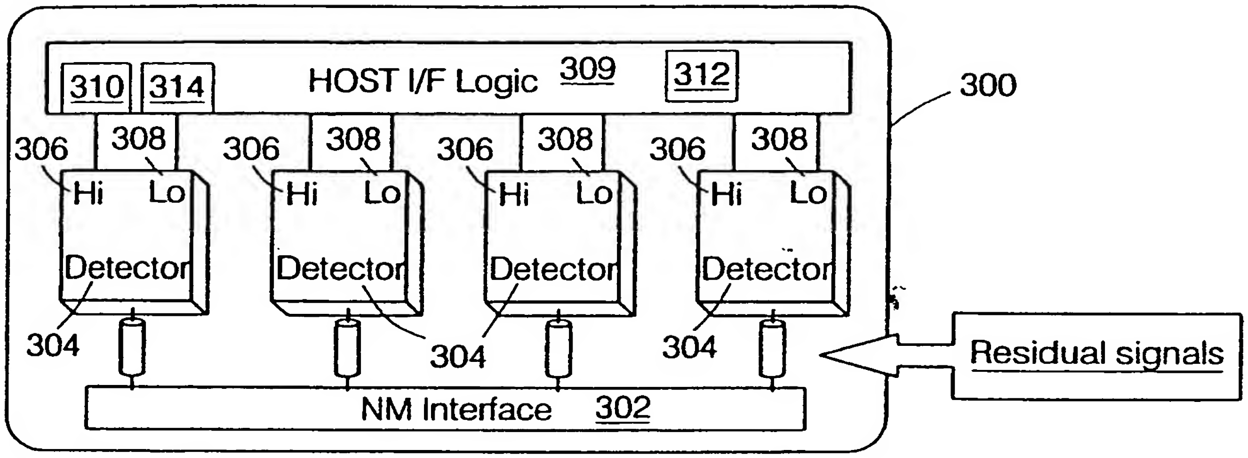

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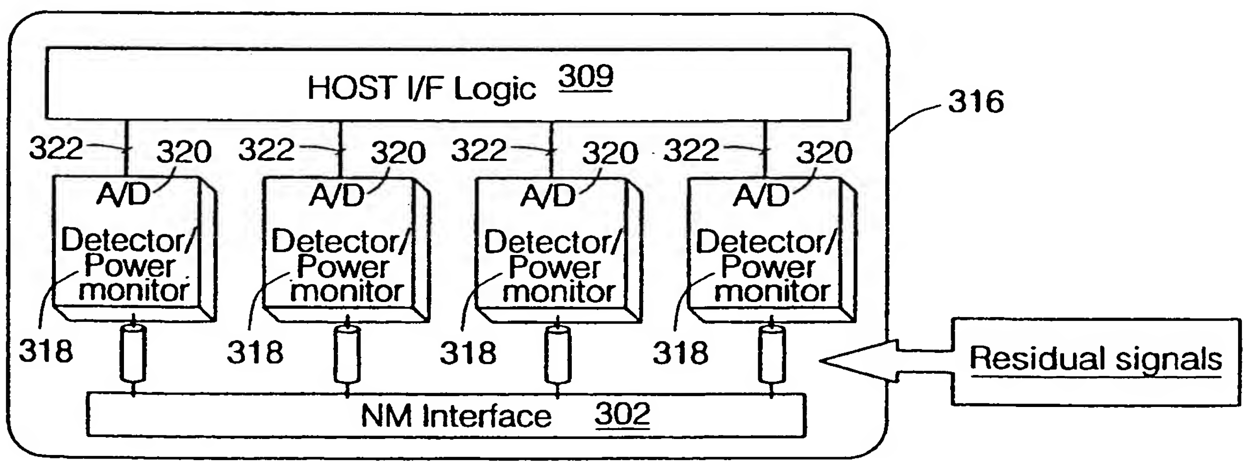
306
308
Hi
Lo
Detector
304
Residual signals
NM Interface 302

FIG. 17



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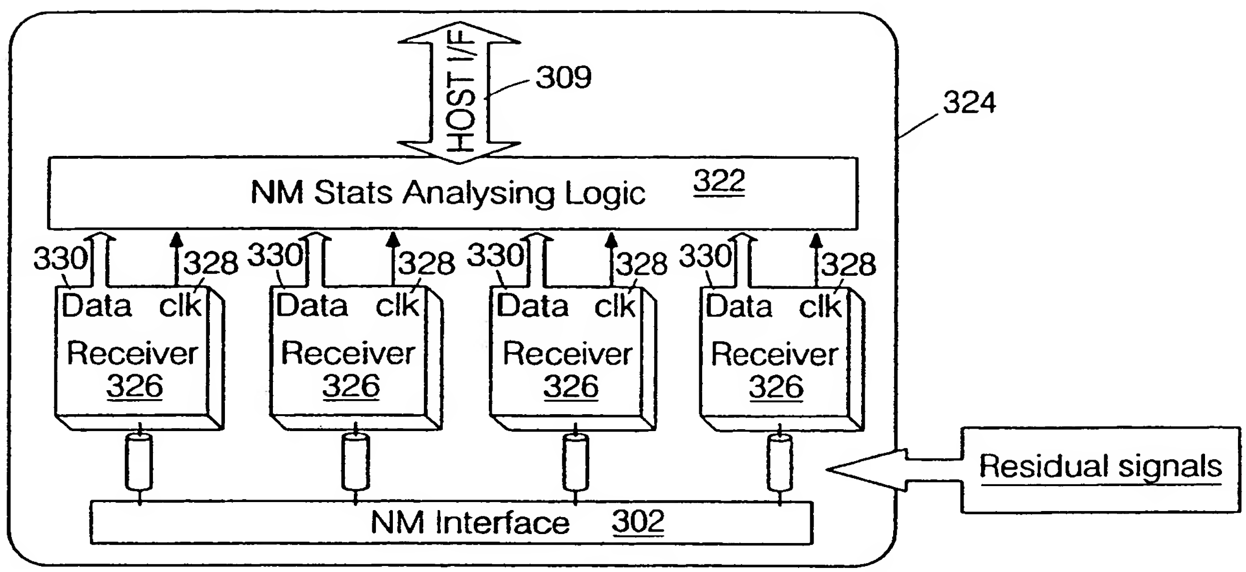
A/D
Detector/
Power
monitor
318
Residual signals
NM Interface 302

FIG. 18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330
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Receiver
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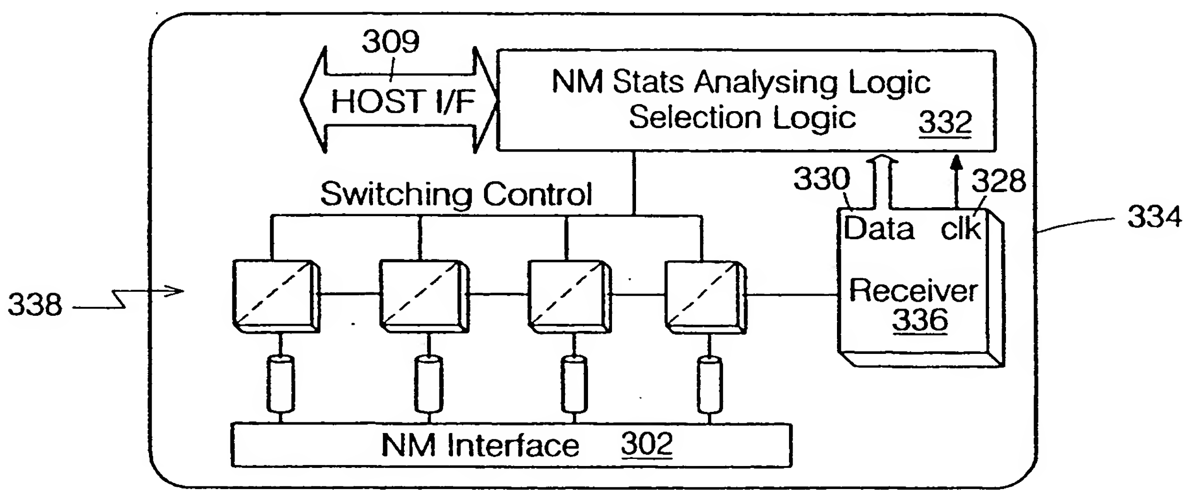
Residual signals
NM Interface 302

FIG. 19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Switching Control
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Receiver
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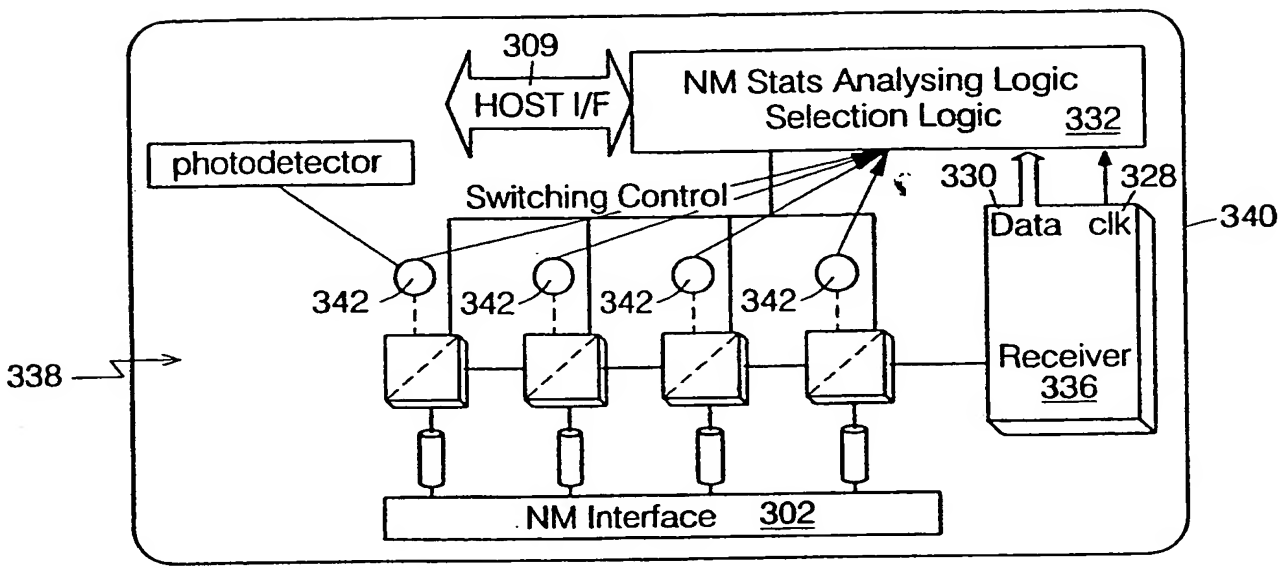
NM Interface 302

FIG. 20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Receiver
336
NM Interface 302

FIG. 21

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL00/00426

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :G02B 6/28; HO4J 14/02
US CL : 385/24, 37, 41; 359/152, 163
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/24, 37, 41; 359/152, 163

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P	US 6,108,471 A (ZHANG et al.) 22 August 2000 (22/08/00) entire document.	1-69
Y	US 5,825,949 A (CHOY et al.) 20 October 1998 (21/10/98), entire document.	1-69
Y	US 5,121,231 A (JENKINS etr al.) 09 June 1992 (09/06/92) entire doucment	1-69

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 DECEMBER 2000	08 JAN 2001

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	M. GELLNER
Facsimile No. (703) 305-3230	Telephone No. (703) 305-3303